ESTABLISH POLICIES AND PROCEDURES FOR USE OF SUBGRADE STABILIZATION IN MICHIGAN

Report No. SPR-1733

MDOT CONTRACT NO. 2019-0309/Z4

FINAL REPORT

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March 7, 2024

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. SPR-1733	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Establish Policies and Procedures for Use of Subgrade Stabilization in Michigan		**5. Report Date** March 7, 2024
		6. Performing Organization Code N/A
7. Author(s) Nishantha Bandara, Ph.D., P.E., Elin Jensen, Ph.D., and Stephen Sebesta		**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Lawrence Technological University 21000 West Ten Mile Road Southfield, MI 48075 Texas A&M Transportation Institute 1111 RELLIS Parkway Bryan, TX 77807		**10. Work Unit No.** N/A **11. Contract or Grant No.** Contract 2019-0309 Z4
12. Sponsoring Agency Name and Address Michigan Department of Transportation Research Administration 8885 Ricks Road P.O. Box 33049 Lansing, MI 48909		**13. Type of Report and Period Covered** Final Report, October 1, 2021–September 30, 2023 **14. Sponsoring Agency Code** N/A
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Michigan Department of Transportation research reports are available at www.michigan.gov/mdotresearch.		

16. Abstract

The benefits of subgrade stabilization have long been identified by many government and private highway agencies. Subgrade stabilization can accelerate construction by eliminating the need to remove and replace soft and wet subgrade soils. This research study aimed to develop comprehensive guidelines for subgrade stabilization project site selection, mix design, and construction. A comprehensive literature review, a survey of Michigan and other state departments of transportation practices, and interviews of personnel experienced with subgrade stabilization were conducted during this study. Results indicated that the most common stabilizers used for subgrade stabilization included lime and cement, but some agencies used other materials such as fly ash, cement kiln dust, or lime kiln dust. Based on the broader findings, comprehensive guidelines for site evaluation and selection were developed during this study. A mix design guidance document was also developed to facilitate the review of contractor-developed mix designs for subgrade stabilization projects by MDOT engineers. A decision tree was included in these guidelines to support the preliminary selection of stabilizers based on site-specific geotechnical investigation results. Finally, a comprehensive construction guidance document was developed to guide MDOT engineers and construction staff through the important steps for subgrade stabilization, including selection of proper equipment, construction of a test strip, and performance of quality control/quality assurance processes. A construction specification for chemically stabilized subgrades was also developed for use in future subgrade stabilization projects. An evaluation of pavement design parameters was conducted using the AASHTOWare Pavement ME Design software to determine the sensitivity of pavement performance to geotechnical inputs. MDOT can readily implement some of the recommendations from this study. Other recommendations require further study before they can be considered for inclusion in specifications or special provisions.

17. Key Words Subgrade stabilization, construction, pavement, performance, design, lime, cement, fly ash, mechanistic-empirical		**18. Distribution Statement** No restrictions. This document is also available to the public through the Michigan Department of Transportation.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 119	**22. Price** N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

This project was funded by the Michigan Department of Transportation (MDOT). The authors would like to acknowledge Mr. Michael Eacker, MDOT Project Manager, for his continuous assistance and support during this project. The authors would also like to acknowledge the MDOT Research Advisory Panel members, including Mr. Andre Clover, Dr. Christopher Byrum, Mr. Justin Schenkel, Mr. Brandon Wegener, Mr. Christopher James, and Dr. Fawaz Kaseer, for their continuous support. Finally, the authors would like to acknowledge the staff and students from Lawrence Technological University, including Nancy Windnagle (Administrative Assistant in the Department of Civil and Architectural Engineering), Priyadharshini Kumar (graduate student), and Justin Przeslawski, Karly Scharf and Natalia Piotrowski (undergraduate students), for their assistance during the literature review and other tasks.

RESEARCH REPORT DISCLAIMER

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EXECUTIVE SUMMARY

Chemical type subgrade stabilization has been used in pavement construction since the 1970s. Although the Michigan Department of Transportation (MDOT) has used chemically stabilized subgrades in a few roadway reconstruction projects, widespread use of subgrade stabilization where it could be used is not occurring at present. The costs for typical undercutting and replacing with high quality sand backfills has increased over the years and good clean undercut sands are becoming less available. Therefore, MDOT has recognized the importance of providing guidance on chemical subgrade stabilization project selection, mix design, and construction as an alternate treatment. The MDOT has also recognized the importance of developing a construction specification for chemically stabilized subgrades and evaluating the effects of pavement design inputs for stabilized pavement layers. To address these objectives, the research team gathered information through a literature review, a survey of practitioners in other states regarding guidelines and specifications for stabilized subgrades, and interviews with MDOT staff and consultants who have expertise in subgrade stabilization.

The literature review and survey of other states' practices showed that several states including Ohio, Indiana, Texas, and California have well-established guidelines and specifications for chemical type subgrade stabilization. The MDOT guidance documents for site selection, mix design, and construction, as well as the construction specification for stabilized subgrades, were developed based on those existing state standards. Additional guidance from the National Lime Association, Portland Cement Association, Federal Highway Administration, and National Cooperative Highway Research Program contributed to developing the guidance documents and construction specifications.

Pavement design inputs for stabilized subgrades were evaluated using the AASHTOWare Pavement ME Design software. The evaluation used recent MDOT calibration parameters and recommended MDOT inputs (e.g., weather, material properties, traffic, etc.). Sensitivity analysis of the software inputs for a 12-inch stabilized subgrade layer, including the resilient modulus (M_R), liquid limit (LL), plasticity index (PI), hydraulic conductivity (k), and percentage passing No. 200 sieve (P200), was performed during this research. The results showed that the geotechnical parameters, LL, PI, P200, and k had no significant effects on the predicted pavement performance from flexible pavement distress models. However, these geotechnical parameters significantly affect the predicted performance from rigid pavement distress models. The M_R of the stabilized layer had a moderate impact on the flexible pavement models, but only a minimal impact on the rigid pavement models. Therefore, since changes to the geotechnical parameters resulting from subgrade stabilization are uncertain, but it is expected that subgrade support should improve, without further research, only the effective resilient modulus increase is recommended for use as a model parameter for stabilized subgrades.

CHAPTER 1 INTRODUCTION

Pavement subgrade improvement comes in many forms and is used to achieve target performance levels during a pavement's construction phase and throughout its service life. Procedures defined as *short-term modification techniques* are intended to provide sufficient strength of the subsurface layer to function as a construction platform for heavy equipment (i.e., by limiting the deflection under wheel load). Short term modification techniques are typically not included as part of the pavement cross section design. More intensive measures designed to act throughout the pavement service life are defined as *long-term stabilization techniques and* are intended to provide enhanced strength, uniformity, and durability of the subsurface layer over the full life of the pavement (i.e., by reducing susceptibility to frost and high water table actions and by adding a stronger, durable, and additional structural layer immediately over the in situ soil). Long-term stabilized layers are often included as structural layers in the pavement cross section design.

Site-specific soil conditions greatly impact the selection of subgrade improvement techniques. Site exploration aims to quantify the engineering properties of the in-situ soil within the project area as well as determine the presence of ground water, organics, salts, and, in particular, sulfates in the subgrade soils. The American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System is commonly used to classify soils based on particle size and Atterberg limits. The MDOT, however, primarily uses the Unified Soil Classification System (USCS). Non-cohesive soil is typically granular material that derives its strength from friction and interlocking of the grains. Cohesive soil typically contains significant amounts of clay and/or silt and derives much of its strength from internal cohesion and water suction or tension. Silt and clay soils are sensitive to the presence of water. Clay is characterized by a negatively charged alumino-silcate sheets surrounded by and suspended in groundwater containing positively charged ions. Clay has a high specific surface area compared to the specific surface area of silt. Because of these characteristics, the plasticity and cohesive engineering properties of clay are highly sensitive to water , making it subject to softening, shrinkage and swelling. Soils containing significant clay and silt percentages are the types of subgrades that can benefit from chemical stabilization techniques and are a focus of this study.

The effects of soil improvement are typically contained within the top 8 to 20 inches of the exposed subgrade. However, factors such as ground water table fluctuations can give rise to capillary actions that could cause the diffusion of deleterious salts from subsurface layers into the stabilized layer. Therefore, standard practice defined in AASHTO R 13 recommends that soil sampling be performed to a depth of 5 feet below the proposed exposed subgrade elevation (AASHTO, 2012). The required geotechnical evaluation test hole spacing for a designwill vary depending on the uniformity of the site soil conditions. For example, the Texas Department of

Transportation (2019) varies the required subgrade sample spacing from 500 feet to 1 mile depending on soil conditions that are present, with more test holes required for poor subgrades.

1.1 Subgrade Improvement Methods

Table 1.1 lists various subgrade improvement measures including their associated stabilizing actions, typical soil applications, and additional notes. The selection of a subgrade improvement technique is typically guided by the soil classification based on the material characteristics of particle size and Atterberg limits. Focusing on chemical stabilizing agents (e.g., cement, lime, fly ash, and bitumen), several agencies have developed selection guidelines based on soil classification. An example of such selection guidelines is shown in Figure 1.1, first published by the U.S. Department of Transportation (USDOT) in 1976 and more recently incorporated into the *Iowa Statewide Urban Design and Specifications* (Iowa State University, 2012). In this figure, the plasticity index (PI) is the difference between the plasticity limit (PL) and the liquid limit (LL) for the subgrade soil.

Table 1.1. Summary of Subgrade Improvement Measures.

Modification/ Stabilization Method	Method Description	Additional Notes
Natural drying	Scarify the soil and allow time to naturally dry	When moisture content is reduced to near optimum levels, soil can be compacted.
Remove and replace	Add granular material to the wet, soft subgrade (or partially replace)	Depth of application ranges from 12 to 24 inches below the grade lines
Geosynthetics	Place one or more layers of geosynthetics above wet and weak soil. The barrier (filter) mitigates pumping of fines into the pavement structure	Allows for compaction of subsequent layers. May improve pavement performance by reducing sublayer stresses and strains.
Mechanical	Mix two or more granular materials to achieve planned particle size distribution and allow compaction	Use in uniform soils changes soil compactability, strength, permeability, and volume stability.
Cement	Use low cement contents (<2%) to change material characteristics from an unbound to a modified bound material with a reduced susceptibility to moisture change (drying out the soil) and improved compaction Use high cement contents to change material characteristics from an	Suitable in granular and fine-grained soils but inefficient in one-sized materials and heavy clays (effectiveness decreases as liquid limit and plasticity index increase). Mixture pH should be >12.1 and sulfates in the soil-cement should be minimal to prevent degradation due to sulfate attacks (e.g., disintegration,

Modification/ Stabilization Method	Method Description	Additional Notes
	unbound to a bound material with cementitious bonds that increase strength and stiffness	expansion, cracking, strength loss, etc.). Organic material should also be minimal because it limits strength gain. Fast setting, high cement contents may increase susceptibility to shrinkage and fatigue cracking Alternative is cement kiln dust.
Lime (dry or slurry)	Mix wet soil with dry lime to reduce moisture content and improve compaction. Apply in warm weather when rain is not forecasted Cementitious bonds may develop if pH>12.6. Slow setting. Soil must also contain natural occurring pozzolanic material	Suitable for cohesive soils. Alters soil characteristics from cohesive to mainly granular; compact after a recommended mellowing period. Limit organic material because it limits strength gain. If needed, add pozzolanic materials Alternative is lime kiln dust.
Fly ash	Fly ash has cementitious and pozzolanic properties; Class C fly ash is cementitious	Slow setting compared to cement. Limit organic material because it limits strength gain.
Cementitious blends (lime/fly ash, slag/lime, slag/lime/fly ash, etc.)	Use Class F fly ash with lime or cement to initiate the hydration process Acts as fillers and slow-setting cementitious blends; can be designed for soil modification or soil stabilization; offers reduced risk of shrinkage cracking compared to cement stabilized material	Can be used where soil is not reactive to lime alone. Alternatives are cement kiln dust and/or lime kiln dust with fly ash.
Bitumen (including emulsions and cutbacks)	Agglomeration (binding) of fine particles decreases permeability and improves cohesive strength	Applicable to granular materials with low cohesion and plasticity. Susceptible to fatigue cracking. Coating of fines decreases sensitivity to moisture.
Bitumen/ cement blends	Agglomeration (binding) of fine particles with some cementitious bonding	Same behavior as bitumen. Cement aids in providing early strength.

Note: Table 1.1 was developed based on information reported by Elsayed (2016), Federal Highway Administration (2014), National Cooperative Highway Research Program (2009), Christopher (2006), and Hicks (2002).

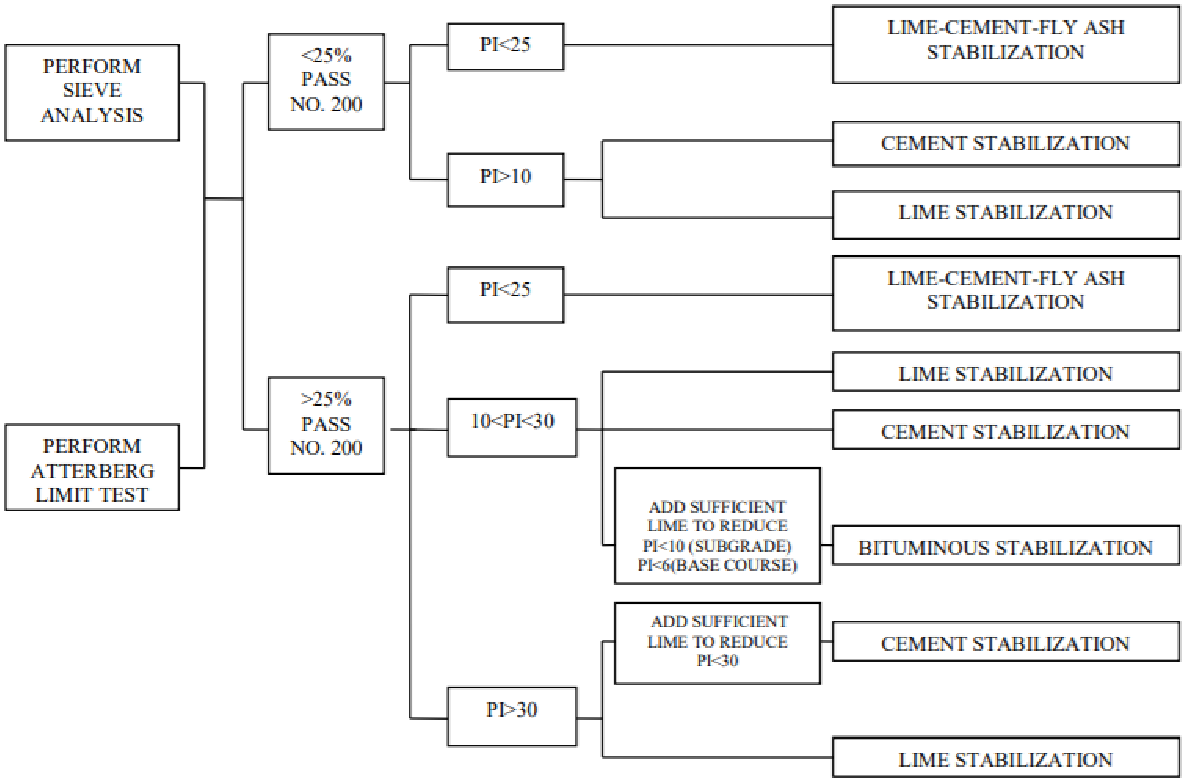

Figure 1.1. Selection Guidelines for Chemical Treatment Options Originally Proposed by the USDOT (Iowa State university, 2013).

1.2 Chemical Stabilizing Mechanisms

This section describes the mechanisms by which the most commonly used materials achieve the soil stabilizing effects, as discussed in Table 1.1. The terminologies associated with the stabilizing mechanisms include hydration and cementitious bonds, pozzolanic behavior, slaked lime/hydrated lime, and agglomeration and binding.

1.2.1 Hydration and Cementitious Bonds

Hydration of cement is a complex process that involves the reaction of finely crushed, calcium-rich cement minerals and water. The hydration products, or calcium silicate hydrates, are responsible for the cementitious bonds. The hydration process is controlled by the cement's chemical composition and fineness and, in particular, the temperature at which it reacts with water. On average, the temperature of the materials and the ambient temperature must be at a minimum of 40–42°F for the hydration process to begin. The hydration process increases exponentially with increasing temperature. Cement hydration is an exothermic process (i.e., releasing heat), which allows the hydration process to continue at lower temperatures. Stabilizing operations are to be performed at above freezing temperatures.

1.2.2 Pozzolanic Behavior

Pozzolan is a siliceous material. At room temperature, pulverized pozzolan reacts with calcium hydroxide and water to form a cementitious hydration product (calcium silicate hydrate). Fly ash (FA) is a pozzolanic material with a grain size distribution similar to that of ordinary cement. When mixed with a coarser material, the fly ash particles fill the voids in the existing soil, and the calcium then activates the pozzolanic reaction. Typically, Class C fly ash contains 3–6 percent calcium oxides, which is often adequate to initiate the pozzolanic reaction. Class F fly ash lacks calcium, and in such cases, supplemental materials such as lime, lime kiln dust (LKD), cement, or cement kiln dust (CKD) can be added up to about 20–30 percent of the FA by weight (National Cooperative Highway Research Program, 2009).

1.2.3 Slaked Lime/Hydrated Lime

Limes—in the form of calcium oxide, quicklime, or LKD—react with the free water in the soil to form calcium hydroxides, generating a significant amount of heat. Calcium hydroxides are called slaked lime or hydrated lime. The purity of the lime controls the rate of the slaking reaction; the resulting process could be fast, medium, or slow. As the lime-soil mixture dries, compaction can take place. Mellowing or conditioning is often recommended prior to compaction. If the pH is ≥12.5, pozzolanic reactions with alumina and silicates can occur over time to form cementitious bonds between the soil particles. A second process taking place is the exchange of cations between the lime and clay soils. These reactions change the texture and plasticity of the soil. The development of cementitious bonds is a prerequisite to long-term strength and stabilization.

1.2.4 Agglomeration and Binding

Bitumen is a black viscous mixture of hydrocarbons, typically obtained as the residue from petroleum distillation. The bitumen binds the granular particles together, and the bonding effect provides the mechanical strength and reduced permeability of the stabilized soil. The mixture of soil and bitumen behaves like asphalt, as a single mass or agglomeration.

1.3 Research Approach

The primary objectives of this project included the following:

- Establish site-specific criteria based on soil type, drainage characteristics, traffic levels, etc. that indicate whether subgrade stabilization should be considered. These criteria may differ for fine-grained and coarse-grained soils. These criteria may also differ depending on short-term and long-term goals (i.e., establishing a short-term solid construction platform versus stabilizing for long-term performance). Cost/benefit analysis may also be a part of the decision process.

- Establish the best materials to use as stabilizing agents for fine-grained and coarse-grained soils.
- Propose mix design methods, mix design criteria (e.g., strength), construction methods, and testing protocols/criteria for construction acceptance and describe their recommended use. A decision matrix or table format is desirable.
- Establish inputs for stabilized subgrades that can be incorporated into AASHTO's recent mechanistic-empirical pavement design methods (2004), as well as AASHTO's traditional pavement design methods outlined in the *Guide for Design of Pavement Structures* (1993).

To achieve the above objectives, the following seven tasks were performed by researchers:

1. Searched and reviewed literature with a particular emphasis on research already completed in Michigan (e.g., Bandera et al., [2016], etc.).
2. Reviewed MDOT stabilized subgrade specifications and determined how stabilized subgrade is accounted for in pavement design. This task was expanded to include subgrade stabilization practices in other states as well.
3. Interviewed MDOT personnel to gather lessons learned from previous stabilized subgrade projects. This task was expanded to include personnel from other state departments of transportation as well.
4. Developed specifications.
5. Developed guidance for project/site selection, mix design, and construction.
6. Finalized pavement design inputs for the stabilized subgrades.
7. Drafted the final report.

CHAPTER 2 LITERATURE REVIEW

A comprehensive literature review was conducted as two subtasks: review research completed in Michigan (Task 1a), and review research completed outside Michigan (Task 1b).

2.1 Research Completed in Michigan

Two main research reports completed in Michigan related to subgrade stabilization include the following:

- *Cement Kiln Dust Stabilized Test Section on I-96/I-75 in Wayne County* (Report No. R-1530) (Bandara & Grazioli, 2009).
- *Performance Evaluation of Subgrade Stabilization with Recycled Materials* (Report No. RC-1635) (Bandara et al., 2016).

The first report (Report No. R-1530) details the construction of a cement kiln dust (CKD) stabilized test section along I-96/I-75 in Wayne County, Michigan. The report describes the test section construction procedures, associated construction specifications, and field strength gain test results. Dynamic cone penetrometer (DCP) test results showed a substantial increase in subgrade soil strength through CKD stabilization over the lime stabilized areas constructed outside the test section. On average, CKD stabilized areas had an 885 percent higher strength in terms of California Bearing Ratio (CBR) estimated from the DCP testing relative to the existing soil strength. Lime stabilized areas had a 531 percent higher strength on average.

The second report (Report No. RC-1635) was aimed at identifying short-term and long-term advantages and disadvantages associated with subgrade stabilization using recycled materials such as CKD, lime kiln dust (LKD), fly ash (FA), concrete fines, and mixtures of LKD and FA. Extensive laboratory testing was conducted to determine the subgrade stabilization suitability of the various recycled stabilizers for common problematic soils found in Michigan. Laboratory tests were performed to determine basic soil properties, appropriate mix designs that included proper stabilizer percentages for each soil type, pavement design parameters based on California bearing ratio (CBR) test results, and durability of stabilized subgrade sections based on laboratory freeze/thaw test results. A limited field investigation was performed to assess the in situ performance of stabilized subgrades. Based on the findings from both investigations, stabilizers were selected for long-term subgrade stabilization for different soil types, and their associated pavement design inputs were determined. A design matrix with cost considerations was also developed to aid the selection of subgrade treatment options.

2.2 Research Completed Outside Michigan

A comprehensive review of available materials, methods, and protocols for mix designs for subgrade and base stabilization was reported in the *Recommended Practice for Stabilization of Subgrade Soils and Base Materials* (National Cooperative Highway Research Program, 2009). This report mainly focused on traditional stabilizers (e.g., Portland cement, lime, and fly ash) although subgrade stabilization using byproducts was also mentioned in the document. This report provided protocols for stabilizer selection, laboratory verification, and mix design for commonly used traditional stabilizers. Guidance was provided in the form of a decision tree (Figure 2.1) to aid in the selection of chemical stabilizers for specific types of subgrade soils.

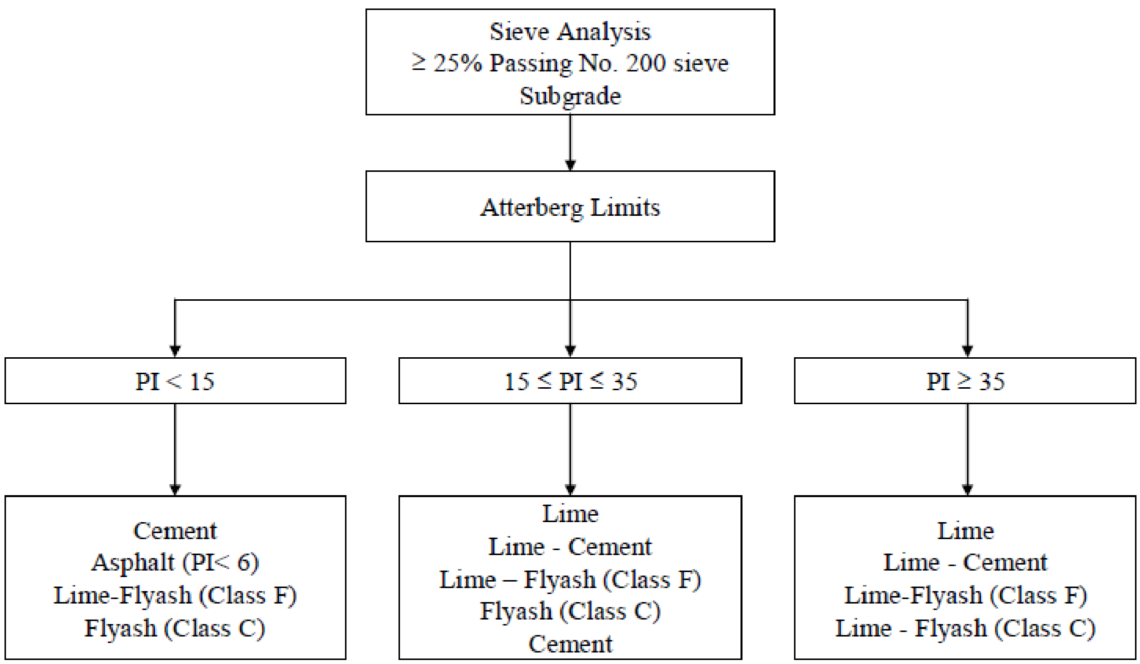

Figure 2.1. Decision Tree for Selecting Stabilizing Agents for Subgrade Soils (National Cooperative Highway Research Program, 2009).

2.2.1 Lime Stabilization

The mix design guidelines for lime stabilization given in the National Cooperative Highway Research Program (2009) report were based on a National Lime Association protocol. This method was designed for long-term strength gain and durability of lime stabilized subgrades.

Soil Evaluation

Soil evaluation consists of determining the PI and percent passing a No. 200 sieve. Soils with a PI of 15 or above and a minimum percent passing No. 200 sieve of 25 percent are suitable for lime stabilization. This protocol also recommends testing for organic content and water-soluble sulfate content. If the water-soluble sulfate content exceeds 3,000 ppm, a swell test should be performed to evaluate the degree of expansion. Remedial actions during construction should be implemented as required.

Optimum Lime Content

The first step required to determine the optimum lime content for subgrade stabilization is based on the Eades and Grim pH test, detailed in standard specification ASTM D6276-19 (ASTM International, 2019b). This test method determines the amount of lime needed to achieve a pH value of 12.45 at 25°C (77°F). The goal of this test is to determine the amount of lime necessary to achieve long-term pozzolanic reactions. However, the mix design guideline recommends that the lime content be validated with strength testing.

Moisture-Density Relationship

Lime changes the optimum moisture content and maximum dry density of the soil mixture. Therefore, moisture-density testing is an important element in construction specifications for soils stabilized with lime. These moisture-density tests are conducted on a soil-lime mixture prepared with the optimum lime content determined by the Eades and Grim pH test (ASTM International, 2019b).

Sample Fabrication and Curing for Compression Testing

For the compression testing, triplicate samples are prepared using Procedure B in standard specification ASTM D5102-96 (ASTM International, 2017b), with the optimum lime content determined by the Eades and Grim pH test (ASTM International, 2019b). Samples within ±1 percent of the optimum moisture content (OMC) are prepared. Additional samples with lime contents 1 and 2 percent higher than the optimum lime content are prepared to verify through testing that the optimum lime content produces the required compressive strength.

After compaction, the samples are wrapped in plastic and stored in an airtight plastic bag containing about 10 ml of water and then cured for 7 days at 40°C (104°F). This accelerated curing procedure provides sufficient moisture and time for strength gain from the pozzolanic reactions between the lime and clays. However, this protocol recommends curing a separate set of soil-lime specimens for strength testing at 28 days.

Once the specimens are cured, they are prepared for capillary soaking by removing them from the plastic bags/wrap and rewrapping them in wet absorptive fabric. During the capillary soaking process, these samples are placed on porous stones. The porous stones are submerged in water with the water level maintained at the top of the porous stones. Capillary soaking should continue until the moisture front moves to the top of the sample or until the moisture front becomes stationary.

Unconfined Compressive Strength Testing

Following capillary soaking, unconfined compressive strength (UCS) tests are performed in accordance with Procedure B in standard specification ASTM D5102-96 (ASTM International, 2017b). For long-term soil stabilization, the UCS value should meet the requirements listed in Table 2.1.

Table 2.1. Recommended UCS Values for Lime Stabilization (National Cooperative Highway Research Program, 2009).

Anticipated Stabilized Layer Application	Compressive Strength Recommendations for Different Anticipated Conditions			
	Extended Soaking	Annual Freeze/Thaw Cycles		
	8 days (psi)	3 cycles (psi)	7 cycles (psi)	10 cycles (psi)
Rigid pavement	50	50	90	120
Flexible pavement (>10 inches)	60	60	100	130
Flexible pavement (8–10 inches)	70	70	100	140
Flexible pavement (5–8 inches)	90	90	130	160

If the mix designs use more than one lime content, the design with the lowest amount of lime satisfying the above requirements should be used as the design lime content. If none of the lime contents meet the requirements in Table 2.1, either additional lime or pozzolans should be added to the mix design, or the design should be considered for subgrade modification rather than stabilization.

Volume Change Measurements for Expansive Soils

The samples prepared for UCS testing can also be used for volume change measurements. Vertical and circumferential measurements of samples before and after capillary soaking are taken to evaluate the volume change between dry and soaked conditions. Three-dimensional expansions of 2 percent or less are considered acceptable. It should be noted that this test procedure is only applicable to expansive soils such as high plasticity clays.

2.2.2 Cement Stabilization

Cement has been used to stabilize most soil types except soils with high organic contents, highly plastic clays, or poorly reacting sandy soils. Cement stabilization is limited by the shorter mixing time (usually not more than 2 hours) before the initial set of the cement. The Portland Cement Association (PCA) recently published a *Guide to Cement-Stabilized Subgrade Soils* to aid mix design when using cement for soil stabilization (Portland Cement Association, 2020). This guide includes a decision tree for selecting cement as a subgrade stabilization material (Figure 2.2).

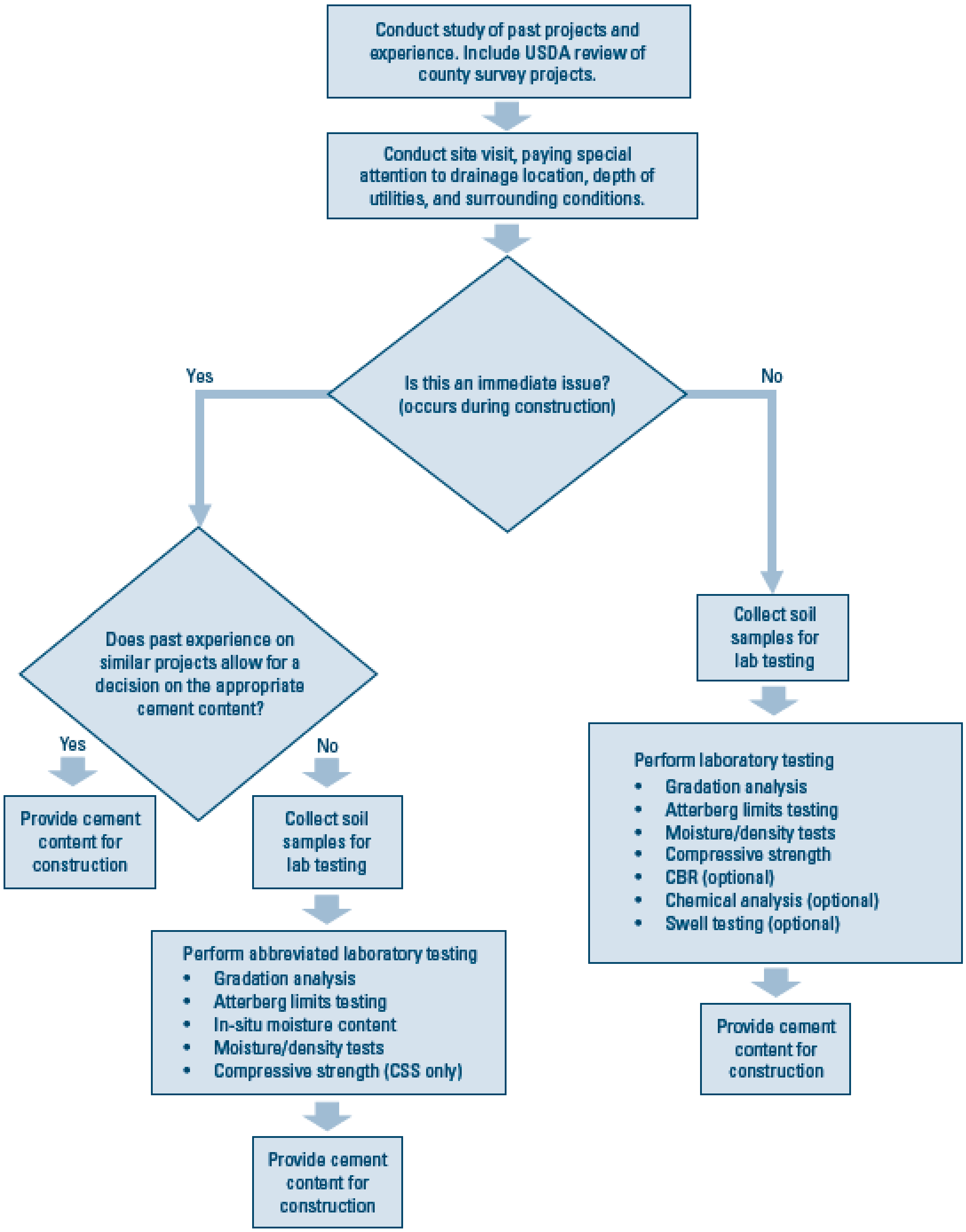

Figure 2.2. Decision Tree for Selecting Cement as a Subgrade Stabilizer (Portland Cement Association, 2020).

Step-by-Step Guidelines for Cement Stabilization Mix Design

The PCA guide also provides the following step-by-step guidelines for cement stabilization mix design (Figure 2.3).

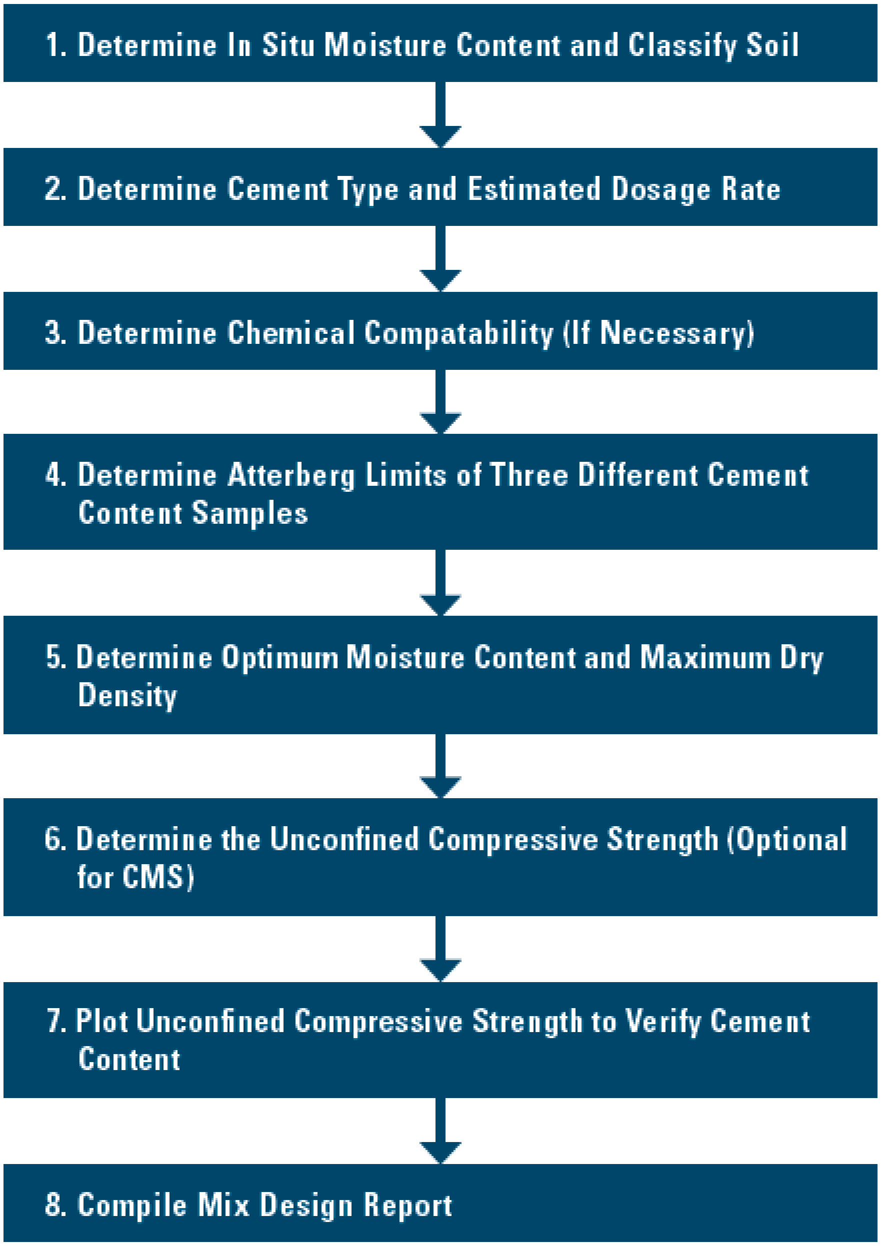

Figure 2.3. Mix Design Steps for Cement Stabilization (Portland Cement Association, 2020).

Preliminary Estimate of Cement Content

The PCA guide recommends a cement content for cement stabilized subgrade (CSS) of 3–6 percent of the dry unit weight of the untreated material. These cement requirements are preliminary estimates only and must be verified and modified based on the results of strength, durability, and/or other laboratory tests.

Chemical Compatibility

As required, the chemical compatibility between the soil and cement can be investigated. The degree of testing depends on the performance criteria that must be met. Tests for expansive characteristics, stability, sulfate content, soil pH, and organic content can be conducted to determine the compatibility of the soil with the cement quantity and type chosen for the CSS application.

Atterberg Limit Testing for Three Different Cement Content Samples

Atterberg limit testing should be performed on CSS samples with varying cement contents. It is important that the testing be completed within 1 hour of mixing.

Moisture-Density Relationship

The next step in the mix design process is to determine the OMC and maximum dry density (MDD) of the CSS, or the soil mixture's moisture-density relationship. These are important properties for estimating strength gain and compaction effort. Determining the OMC, MDD, and percentage of cement for the subgrade to be treated is critical for obtaining the desired moisture and density of the CSS mix. This information is also critical for quality control purposes during the construction phase to ensure adequate compaction, which directly relates to the strength and performance of the cement stabilized subgrade.

Unconfined Compressive Strength Testing

The preparation and curing of samples should be performed according to standard specification ASTM D1633-17 (ASTM International, 2018a). This test procedure requires curing the CSS samples in a moist room and then immersing them in water for 4 hours prior to testing. Generally, 7-day UCS values of CSS mixtures range from 100 to 300 psi.

2.2.3 Fly Ash Stabilization

The *Recommended Practice for Stabilization of Subgrade Soils and Base Materials* (National Cooperative Highway Research Program, 2009) provided some guidance regarding fly ash stabilization. Fly ash is a byproduct of coal burning in power plants and is an excellent product for soil stabilization. There are two types of fly ash: Class C and Class F. They differ depending on the amount of available free calcium. Class C refers to self-cementing fly ash with sufficient free calcium to react with soil in the presence of water (more than 20 percent lime). On the other hand, Class F fly ash has a low concentration of free calcium and requires an additional agent, such as lime or cement, to initiate the formation of cementitious reaction products. Due to their complex stabilization mechanism, the physical properties of materials treated with FA should be tested prior to use for soil stabilization. The availability of fly ash for soil stabilization is dependent on market availability and should be considered when deciding to use FA for soil stabilization.

Class C Fly Ash Mix Design

Currently, no standard test procedures exist for the mix design of Class C fly ash stabilization. However, two important design considerations should be addressed: (1) the time delay when mixing and compacting fly ash-soil mixtures due to high rates of hydration in Class C fly ash materials and (2) the moisture content at which the maximum strength is achieved. Generally, the optimum moisture content for strength gain ranges from 1 to 8 percent below the optimum moisture content for maximum dry density.

The first step in the mix design procedure is establishing moisture-density relationships for each soil type at different FA contents. Once the optimum moisture content for the mix is determined, the moisture-strength relationship is established by using different moisture levels below optimum to determine the moisture content at which the maximum strength is achieved. Test specimens are cured for 7 days at 100°F and then immersed in water for 4 hours or subjected to capillary soak for 24 hours, similar to the approach used in the soil-lime mix design procedure.

Class F Fly Ash Mix Design

When Class F fly ash is used for soil stabilization, an activator such as lime or cement (or LKD or CKD) is required to initiate hydration. The mix design process includes selecting a proper FA content and determining an optimum moisture content and a maximum dry density for the soil-FA mixture. Generally, five different samples with varying FA contents, starting from 6 to 20 percent (by weight), are used. Mixes are molded to determine optimum moisture content according to standard specification ASTM C593-19 (ASTM International, 2019a). The dry density of each mix is also determined. To account for materials lost during field mixing, an additional 2 percent FA is added, above the amount that produces the maximum density and optimum moisture content.

Optimal activator content is determined by trial and error. Typically, one part lime to three parts FA (1:3 ratio) or one part lime to four parts FA (1:4 ratio) are used. If LKD or CKD are used as activators, higher ratios are required based on the free lime content in the kiln dusts.

The same curing procedures and compressive strength tests used for Class C fly ash mixtures are used for Class F fly ash mixtures.

2.2.4 Pavement Design Inputs for Stabilized Subgrade Layers

This section summarizes the literature review results for key pavement design inputs related to soil mixture characteristics and properties that are influenced by the type and content of stabilizing chemicals.

Studies of In Situ Pavement Structures

A study conducted by the Kentucky Transportation Center (Hopkins et al., 2002) investigated the bearing strength, durability, structural stiffness, economics, and performance of pavements with subgrades stabilized with different chemical mixtures. These stabilizing agents included hydrated lime, Portland cement, a combination of hydrated lime and Portland cement, and byproducts such as LKD and atmospheric fluidized bed combustion ash. Researchers evaluated 14 roadway sites containing 20 different treated subgrade sections with different stabilizing agents. At the time of the study, these projects ranged in age from 8 to 15 years. Within these projects, more than 450 soil borings were performed including in situ CBR tests. Index tests and resilient modulus (M_R) tests were performed on collected samples. Furthermore, falling weight deflectometer (FWD) tests were performed to evaluate in situ pavement characteristics, such as subgrade moduli values. Based on the in situ CBR tests, Table 2.2 presents the results reported based on the 85th percentile test values.

Table 2.2. In Situ CBR Values (85th Percentile) and Structural Layer Coefficients (Hopkins et al., 2002).

Chemical Admixture	In Situ CBR Value (85th Percentile)	Structural Layer Coefficient
Hydrated lime	27	0.106
Portland cement	59	0.127
Hydrated lime/Portland cement	32	0.11
Lime kiln dust	24	0.10
Atmospheric fluidized bed combustion ash	9	0.08
Untreated soil subgrade	2	-

Practical Application Considerations of Pavement Design Input Parameters

A more recent study conducted for the Ohio Department of Transportation (Sargand et al., 2014) aimed to develop guidelines for incorporating chemical stabilization of the subgrade into pavement design and construction practices. The study included a survey of departments of transportation in all U.S. states and Canadian provinces. Twenty-six states and three provinces responded. Figure 2.4 shows the types of chemicals used for subgrade stabilization based on the survey results.

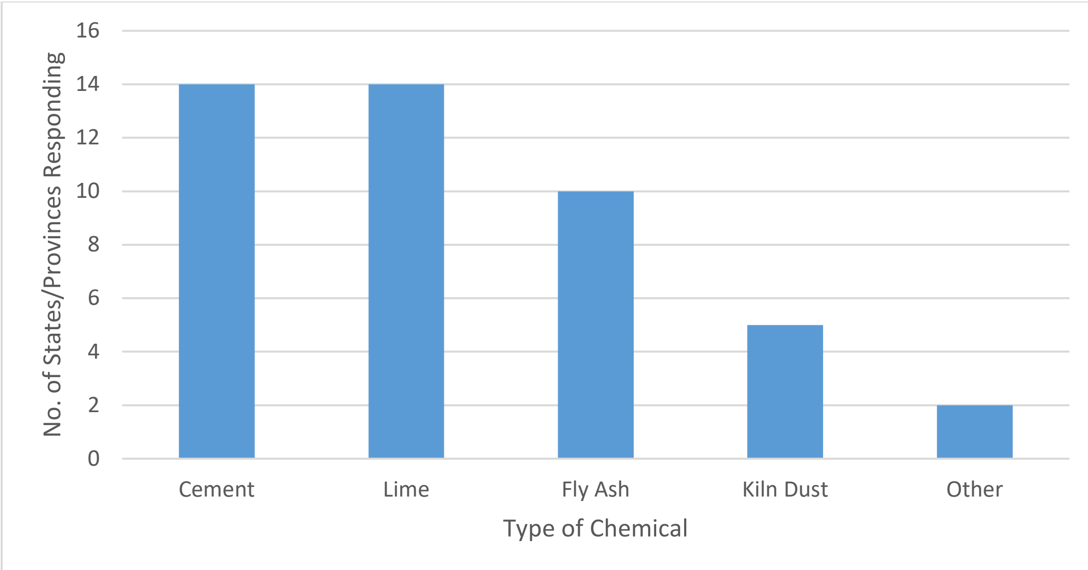

Figure 2.4. Types of Chemicals Used for Subgrade Stabilization by Various U.S. States and Canadian Provinces (Sargand et al., 2014).

This survey also captured how some states/provinces incorporate the stabilized subgrade into the pavement design process, typically by modifying the structural layer coefficient or the resilient modulus (Table 2.3). In addition, this survey captured the strength criteria used by some states/provinces for design and acceptance of the stabilized sections (Table 2.4).

Table 2.3. Incorporation of Stabilized Subgrade into the Pavement Design Process by State (Sargand et al., 2014).

State	Cement Stabilized		Lime Stabilized			Fly Ash Stabilized	
	Structural Layer Coefficient	Other	Structural Layer Coefficient	Resilient Modulus	Other	Structural Layer Coefficient	Resilient Modulus
Arkansas	0.2		0.07				
Kansas	0.11		0.11			0.11	
Kentucky	0.1		0.08				
Maryland	Base: 0.15–0.25 Subgrade: 0.05–0.07						
Mississippi	0.2					0.2	
Nebraska				30,000 psi			30,000 psi
North Carolina		Structural number=1			Structural number=1		
South Carolina	0.15						

Table 2.4. Minimum UCS Criteria for Design/Acceptance of Stabilized Subgrade by State (Sargand, et al., 2014).

State	Cement	Lime	Fly Ash	Kiln Dust
Arkansas	400 psi at 7 days			
Illinois	500 psi at 7 days	150 psi at 48 hours		
Kentucky	Cores: 80 psi at 7 days	Cores: 80 psi at 7 days		
Maryland	Base: 450 psi at 7 days Subgrade: 300 psi at 7 days	Base: 450 psi at 7 days Subgrade: 300 psi at 7 days		
Michigan				125 psi (optimum CKD) at 7 days
Mississippi	300 psi	CBR 20	400 psi	
Nebraska	No minimum, test the specific soil with varying percentages of lime or fly ash and optimize strength versus economy			
North Carolina	200 psi at 7 days	58 psi at 7 days		
Ohio	100 psi at 8 days and minimum increase of 50 psi over unstabilized	100 psi at 8 days and minimum increase of 50 psi over unstabilized		100 psi at 8 days and minimum increase of 50 psi over unstabilized
Oklahoma	Minimum increase of 50 psi over unstabilized at 7 days	Minimum increase of 50 psi over unstabilized at 7 days	Minimum increase of 50 psi over unstabilized at 7 days	Minimum increase of 50 psi over unstabilized at 7 days
South Carolina	300 psi at 8 days			
Texas	Road mix: No requirement Plant mix: 175 psi	No requirement	No requirement	

The main objective of Sargand's study was to determine how to incorporate the increase in stiffness of stabilized subgrade into the pavement design process. This was achieved by using stabilized pavement sections and a portable seismic properties analyzer, a FWD, coring, and DCP. The results, after analyzing hundreds of stabilized pavement sections in Ohio, confirmed that the structural layer coefficients of the stabilized layer can be incorporated into the flexible pavement thickness design when using AASHTO's *Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials, 1993). Figure 2.5 shows the cumulative frequency of stabilized subgrade layer coefficients for FWD versus DCP values. This chart should be used with an appropriate level of confidence for the pavement structure being designed.

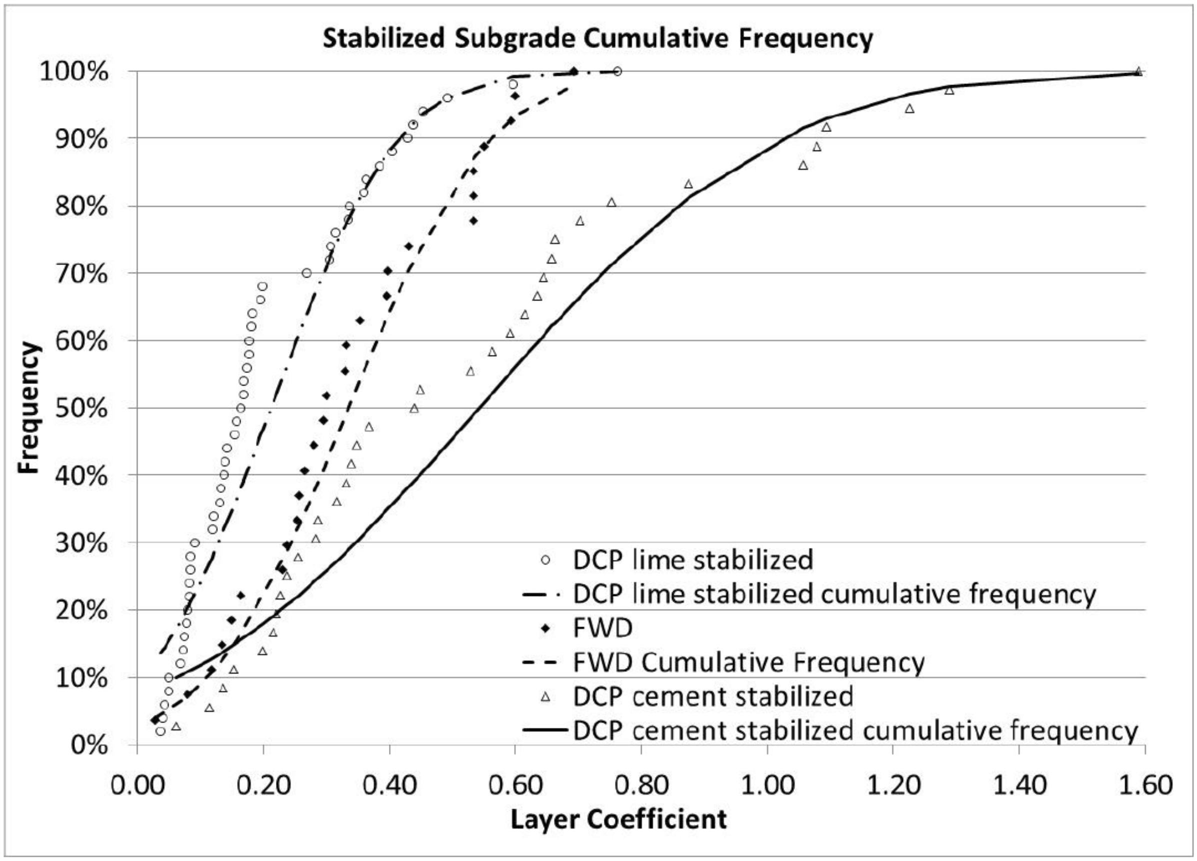

Figure 2.5. Cumulative Frequency of Stabilized Subgrade Layer Coefficients for FWD versus DCP Values (Sargand, et al. 2014).

For mechanistic-empirical (ME) pavement design, Sargand et al. (2014) recommends applying a multiplier to the natural subgrade's resilient modulus to obtain the stabilized subgrade's resilient modulus (Table 2.5).

Table 2.5. Natural Subgrade Resilient Modulus Multiplier to Obtain Stabilized Subgrade Resilient Modulus for ME Pavement Design (Sargand, et al., 2014).

Stabilizing Material	Resilient Modulus Multiplier
Cement	4.7
Lime	3.9

A Minnesota Department of Transportation study, titled *Subgrade Stabilization ME Properties Evaluation and Implementation*, investigated procedures for including stabilized layer stiffness in ME pavement design (Budge, 2012). Based on a literature review, researchers recommended using a resistance factor (RF) based on a ratio of the stiffness of the stabilized material to the stiffness of the native (untreated) materials for pavement design. The RF value for ME design shall have a value less than or equal to 2 and is obtained as follows:

$$RF = \frac{M_r(stabilized)}{M_r(native)} \leq 2 \quad (1)$$

where:

RF=resistance factor for stiffness.
M_r *(stabilized)*=resilient modulus of the stabilized material.
M_r *(native)*=resilient modulus of the native (untreated) material.

Soil Mixture Characteristics and Properties for the Pavement Design Inputs

Field geotechnical reports for stabilized subgrade include the typical characteristics and properties used in quality control and quality assurance such as Atterberg limits, OMC, MDD, UCS, and CBR values. Other parameters that are less frequently tested, such as free swell, gradation, and hydraulic conductivity or permeability, are also important because they are input parameters in the AASHTOWare Pavement ME Design software.

Strength Characteristics of Stabilized Subgrades. The long-term durability of lime stabilization has been documented by Kavak and Baykal (2012). They found that the UCS and elastic modulus for 4 and 12 percent lime stabilized clays were higher at 10 years compared to 28 days. The UCS increased from about 1,000 kPa (145 psi) to about 2,500 kPa (360 psi). The magnitude of the elastic modulus similarly increased.

Rahman et al. (2021) recently conducted a case study on the use of lime, cement, and bentonite stabilized subgrades, where the existing subgrade was silt or silty clay with a low liquid limit. Compared to earlier studies, similar trends showing increasing M_R and CBR values with increasing percentages of stabilizing agents were observed. This study did, however, show superior material performance for lime and cement compared to bentonite for stabilized subgrades.

Low-volume roads constructed on clays with high liquid limits are typically paved when the average daily traffic volume exceeds 5,000. Sirivitmaitrie et al. (2011) reported on three case studies from Arlington, Texas, using 4 percent lime and 4 percent lime followed by 4 percent cement treated subgrades. These sites were constructed in the spring of 2006. The UCS ranged from 87 to 327 kPa (from 12 to 47 psi) for the untreated soils, from 1,395 to 2,288 kPa (from 202 to 332 psi) for the lime treated soils, and from 1,730 to 3,442 (from 250 to 500 psi) for the lime-cement treated soils. Similarly, the M_R increased by a minimum factor of two for the lime treated soils and by a factor of three for the lime-cement treated soils. Field evaluation of the same sites showed that DCP values and surface elevations remained consistent throughout the first 3 years. Field surveys, at a pavement age of 6 years, showed very few cracks on the treated sections, yielding a high rating for the current pavement condition.

Hydraulic Conductivity and Permeability of Stabilized Subgrades. Nalbantoglu and Tuncer (2001) evaluated the hydraulic conductivity of a chemically treated expansive clay. The untreated soil PI was 46, the clay content was 33 percent, the hydraulic conductivity was 4×10^{-12} m/s (1.13×10^{-6} ft/day), and the swell potential was 19.6 percent. Adding lime at rates of 3, 5, and 7 percent increased the 30-day hydraulic conductivity by a magnitude of 100. For example, the hydraulic conductivity increased to 8×10^{-10} m/s (2.26×10^{-4} ft/day) for the 5 percent lime content. Similar, but slightly lower, increases were observed when 15 and 25 percent fly ash contents were used. The combination of 15 percent fly ash with 3 percent lime showed the highest increase in this study.

Guthrie et al. (2012) studied the hydraulic conductivity of cement stabilized granular subgrade materials. The study reported the hydraulic conductivity after the soil mixtures had been subjected to four freeze-thaw cycles. Six different soils were studied, including well-graded gravel with sand, poorly graded gravel with silt and sand, poorly graded sand, silt with sand, poorly graded sand with gravel, and silty sand. The cement content was varied as high, medium, and low, where the low cement content met the 7-day UCS requirements. Using the poorly graded sand material as an example, the hydraulic conductivity decreased from 8.1 to 1.5 to 0.52 ft/day (2.86×10^{-5} to 5.30×10^{-6} to 1.83×10^{-6} m/s) as the cement content increased from 1 to 1.5 to 2 percent. The study proposed regression-based models to predict the hydraulic conductivity after frost exposure. In particular, one of the models predicted the hydraulic conductivity with a coefficient of determination (R^2) of 0.93 based on the USCS using UCS, dry density, percent passing a No. 100 sieve, and particle-size diameters at which 10 and 30 percent are finer, respectively.

Sante et al. (2014) studied a clayish soil that, in its untreated state, had a PI of 30, a sand fraction of 16 percent, and a clay fraction of 44 percent. The soil mixture with 5 percent lime had a hydraulic conductivity of 2.83×10^{-1} ft/day (1×10^{-6} m/s). Further, this study found that the hydraulic conductivity of soil mixtures using hydrated lime could drop up to two orders of magnitude if allowed to dry out within the first 2 days. Soil mixtures stabilized with the more highly reactive quicklime were not as sensitive to drying out because of the fast forming pozzolanic crystals.

Quang and Chai (2015) studied the effects of the percentage of stabilizing agents (lime and cement) on the permeability of stabilized clayish soil. They determined that the permeability of cement and lime treated soils did not change until a critical threshold was reached. Above this threshold, the permeability decreased significantly. For cement treated soils, the threshold was 8 percent; for lime treated soils, the threshold was about 4 percent. The permeability was found to be directly related to the cementitious products filling the intra-aggregate pores, affecting the void ratio and distribution.

Awad et al. (2021) conducted a literature review on the effects of lime on the permeability of stabilized soil, summarizing results from 14 studies on lime modified and stabilized expansive clay soils from several continents. Lime contents ranged from 1 up to 13 percent. The general results showed that the permeability of expansive soils modified with lime increased during the first 7 days of curing and remained constant or slightly decreased as curing times increased. However, for expansive soils stabilized with lime, results showed that the permeability increased during the first 7 days of curing then decreased as curing times increased (because of pozzolanic reactions). Although the permeability decreased during the pozzolanic reactions, it remained higher than the permeability of the untreated soils.

Boardman et al. (2001) suggested using a nondestructive in situ conductivity monitoring technique instead of the standard quality assurance tests. This study considered two different soils: a predominantly kaolinite clay and a predominantly sodium montmorillonite clay. The minimum lime content was 1.5 percent for the first clay type and 7 percent for the second clay type. The study suggested little benefit in adding lime above the minimum lime content value in the short term but significant benefit in the long-term. The conductivity measurements remain consistent for the first 7 days, after which the pozzolanic reactions are expected to occur. Because the pozzolanic reactions cause a reduction in the soluble calcium concentration, the conductivity will continue to decrease with curing.

Grain Size Distribution of Lime Stabilized Subgrades*.* Gidday and Mittal (2020) studied the soil characteristics and properties of a clay stabilized with lime. The clay in the untreated state had a PI of 32, a percent passing a No. 200 sieve of 71 percent, and a clay fraction of 41 percent. Table 2.6 summarizes the results after 7 days of curing and for lime contents from 3 to 9 percent. Note that the stabilized soil mixture exhibited significantly different Atterberg limits as expected, but the soil also demonstrated significant changes in grain size distribution. Zhu et al. (2019) reported similar results related to grain size distributions and Atterberg limits for a silty clay.

Table 2.6. Soil Characteristics of Original and Lime Treated Soils.

Description	Original Soil	Value after 7 Days of Curing			
		3% Lime	5% Lime	7% Lime	9% Lime
Percent passing a No. 4 sieve	100	N/A	N/A	N/A	N/A
Percent passing a No. 10 sieve	95.2	N/A	N/A	N/A	N/A
Percent passing a No. 200 sieve	70.6	50.34	47.26	44.26	40.9
Natural moisture content	34.67	N/A	N/A	N/A	N/A
Specific gravity	2.72	2.7	2.65	2.63	2.6
Gravel size	0	0.46	1.74	2.94	3.26
Sand size	29.4	49.2	51	52.8	55.8
Silt size	29.39	21.62	19.16	23.36	17.3
Clay size	41.21	28.72	28.1	20.9	19.57

Description	Original Soil	Value after 7 Days of Curing			
		3% Lime	5% Lime	7% Lime	9% Lime
LL	77	72	65	58	54
PL	45	47	48	49	50
PI	32	25	17	9	4
AASHTO	A-7-5	A-7-5	A-7-5	A-5	A-5
Group index	26.15	10.79	6.36	2.47	0
USCS	MH	MH	GC	GM	GM
CBR (4-day soak)	3	3.7	4.5	5.2	7.5
UCS (psi)	99.51	132	138	176	202
OMC (%)	23.12	24.66	25.06	27.33	29.43

2.2.5 Other Studies Considering Alternative Stabilizing Chemicals

Saldanha et al. (2018) investigated the use of carbide lime—a byproduct from the production of acetylene gas (C_2H_2) from calcium carbide. The purity of the carbide lime is a function of the manufacturing process. The carbide lime—predominantly a calcium hydroxide (Portlandite) with calcite (calcium carbonate)—is similar to commercial lime. Carbide lime can typically be considered nonhazardous based on the U.S. Environmental Protection Agency's toxicity thresholds but will have high pH values approaching 12.4–12.5.

Kang et al. (2014) conducted a comprehensive study on the use of Class C fly ash and LKD to chemically stabilize a weak low-plasticity clay and a slightly stronger high-plasticity clay with an UCS of 138 kPa (20 psi) and 160 kPa (23 psi), respectively. The study focused on the UCS, M_R, and permanent strain. Short-term and long-term UCS and M_R values for the modified soils were improved by the addition of FA and LKD. Note that the amount of FA (10, 15, and 20 percent) added to the low-plasticity soil impacted the rate of UCS development up to about 14 days. However, the long-term (28-day) strength was similar across all three FA contents, measuring about 500 kPa (72 psi). Consistent with findings in earlier studies, Kang et al. (2014) suggested that strength gain was limited due to the increased risk of shrinkage cracking at FA contents above 15 percent. The addition of 4 and 8 percent LKD also improved the UCS. The most significant strength gain occurred after 14 days. The 28-day UCS reached 275 kPa (40 psi) and 330 kPa (48 psi), respectively.

This study also investigated the effects of chemical stabilization on the M_R, including the effects of deviatoric (shear stress) levels. A power trend was observed for M_R values as a function of curing time under a constant high deviatoric stress and varying confining pressures. The M_R increased from about 50 MPa (7,250 psi) at the start of curing to about 250 MPa (36,250 psi) at 28 days.

Using the 28-day results and the 10 , 15 , and 20 percent Class C fly ash contents for the modified low-plasticity clay, the following linear relationship (with an R^2 of 0.74) was established for the M_R as a function of the UCS:

$$M_r = 0.4968 \times UCS - 36.156 \tag{2}$$

Similarly, the permanent strain was obtained as deformation developed during the initial sample conditioning for the resilient modulus testing at the various deviatoric stress levels. The study found that the FA stabilized soils exhibited significantly lower permanent strains than the LKD stabilized soils. For design considerations where rutting is a controlling parameter, the selection of stabilization agents should also be evaluated using the permanent strain.

Jian et al. (2019) investigated cementitious binders for clayey soils subjected to sulfate attacks. They determined that an alkali-activated ground granulated blast furnace slag, along with sodium silicate and calcium (lime) carbide outperformed a traditional lightweight Portland cement stabilized soil mix in terms of UCS and durability. The alternative cementitious binders remained crack-free after soaking in a Na_2SO_4 solution for 120 days, whereas the lightweight Portland cement stabilized soil exhibited significant cracking after 90 days.

Coban et al. (2021) proposed the use of lime sludge—a byproduct from the lime water softening treatment process—for the stabilization of soil classified as a frost-susceptible, low-plasticity silt. Traditionally, the lime sludge precipitates in lagoons prior to application on agricultural land. In this study, the lime sludge was obtained as a silt pellet with a lime content of about 3 percent. Soil stabilization tests using lime sludge pellets at 4, 8, 12, 20, 30, and 40 percent indicated that a minimum of 20 percent lime sludge was necessary to achieve expectations for short-term modifications. The study also investigated various blended mixes with lime sludge, fly ash, and Portland cement. These additional findings were consistent with earlier studies that considered these stabilizing agents.

Baldovino et al. (2021) also studied blended mixes to stabilize silty soil with recycled glass powder and lime (dolomitic hydrated lime). These mixes demonstrated the ability to achieve significant UCS, often above 1,200 kPa (174 psi), after 28 days. Furthermore, the porosity/binder index—defined as the porosity divided by the volumetric content of pozzolan plus carbide lime—was found to be a critical indicator of a mixture's stabilizing qualities.

Consoli et al. (2018) proposed a general UCS correlation for sandy soil and pozzolan-lime based on the porosity/binder index. Normalizing this index with the lime index, researchers developed an equation that predicts the UCS for any blend of sandy soil and pozzolan-lime that is cured for a specific period based on the performance of only one test. This study demonstrated a comparable alternative to cement stabilized soils using a sustainable binder made from the recycled domestic and industrial waste of ground glass, coal ash, and carbide lime.

CHAPTER 3 REVIEW OF STATE DEPARTMENT OF TRANSPORTATION SUBGRADE STABILIZATION SPECIFICATIONS

This task was conducted as two subtasks: review MDOT's stabilized subgrade specifications and pavement design inputs (Task 2a), and review other states' stabilized subgrade specifications and pavement design inputs (Task 2b).

3.1 Review of MDOT's Stabilized Subgrade Specifications and Pavement Design Inputs

A review of previous MDOT projects constructed using subgrade stabilization revealed multiple iterations of specifications developed for different projects. Table 3.1 summarizes the latest list of MDOT projects that used subgrade stabilization and indicates the availability of special provisions (SPs) to guide construction.

Table 3.1. Michigan Department of Transportation Subgrade Stabilization Projects.

Project Year	Project Number	Project Location	Material(s) Used	Special Provision Status
2005	52803	I-96, M-39 east to Schaefer Rd., Wayne County, MI	Lime	SP *Lime Stabilized Subgrade*, dated 12/07/2004, was provided
2008	37795	I-75/I-96, Vernor Rd. to Michigan Rd., Wayne County, MI	Lime, lime-fly ash, CKD	SP *Lime Stabilized Subgrade*, dated 12/07/2004, was provided
2010	48271	M-84, Bay Rd, Saginaw County, MI	Lime, lime-fly ash	SP *Lime Stabilized Subgrade*, dated 12/07/2004, was provided
2013	47040	M-53, 34 Mile Rd. to Boardman Rd.	CKD or LKD (stabilization omitted due to lack of CKD)	Although stabilization was omitted, SP *Chemically Stabilized Subgrade*, dated 11/12/2010, was provided
2018	117992	US-131, 10 Mile Rd. to 14 Mile Rd.	Cement, lime, lime-fly ash	SP *Chemically Stabilized Subgrade for Job Number 117992*, dated 11/21/2017, was provided
2018	115799	I-69, Ballenger Rd. to Fenton Rd.	Lime	SP *Lime Stabilized Subgrade for Job Number 115799*, dated 3/30/2017, was provided
2020	201437	I-75, 13 Mile Rd. to Square Lake Rd.	Cement	During construction, contractor requested to use subgrade stabilization on a portion of the project
2023	132102	US-24, Grand River Ave. to 8 Mile Rd.	Cement	Draft SP was provided

In general, the construction specifications contained the following sections: materials, equipment, construction, mix design, acceptance, and pay items. Table 3.2 summarizes the construction specifications used in Michigan.

Table 3.2. Summary of Reviewed MDOT Construction Specifications.

Categories	Notes
Stabilizing material	Cement, lime, lime-fly ash, CKD, LKD (CKD and LKD were specified in 1 project)
Selection process for soil modification	Existing granular materials in subgrade must be stabilized using cement or CKD Existing cohesive materials in subgrade must be stabilized using lime, LKD, or a lime-fly ash combination Classification of the existing in-place soils is performed by the regional soils engineer Some specifications directly specify the type of stabilizer to be used in the project
Mix design	Contractor-designed soil mix with cement, CKD, lime, LKD, or a lime-fly ash combination
Required laboratory tests	Soil classification for untreated and treated soils per AASHTO M 145-91 (American Association of State Highway and Transportation Officials, 2021) and ASTM D2487-17e1 (ASTM International, 2020) Moisture-density tests for untreated and treated soils per AASHTO T 99-22 (American Association of State Highway and Transportation Officials, 2022) California bearing ratio lab tests for treated uncured soils per ASTM D1883-21 (ASTM International, 2021) Liquid limit and plastic limit tests per ASTM D4318-17 (ASTM International, 2018b) Eades and Grim pH test for minimum lime or LKD content determination per ASTM D6276-19 (ASTM International, 2019b) Unconfined compressive strength tests for treated and cured soils per ASTM D5102-96, ASTM D1633-17, ASTM D2166-06, and ASTM D3551-17 (ASTM International, 2017b, 2018a, 2010, 2017a)
Equipment	Sheepsfoot or vibratory pad foot roller Steel-wheeled smooth rollers Pneumatic-tired rollers Mechanical spreader Watering equipment Tampers Rotary pulvimixer
Subgrade preparation	Shape existing material to conform to lines and grades shown on plans Remove all deleterious material (topsoil, roots, organic materials, foreign debris, rock fragments larger than 2½ inches, etc.) Dispose of deleterious materials in accordance with the standard specifications
Drainage	Special provisions require adequate drainage during the entire construction period to prevent water from collecting or standing on the area to be stabilized, pulverized, mixed, or partially stabilized No mention of long-term drainage was made in any SP
Stabilization depth	Most often 12 inches, one project had an 8-inch depth
Weather/seasonal considerations	Ambient temperature of 40°F and rising, with seasonal limitations between April 1st and October 31st
Pavement design inputs	Special provisions do not contain information related to pavement design inputs, however, MDOT's Pavement Management Unit has prepared recommendations for stabilized subgrade properties in pavement design (Table 3.3)
Design, construction specifications, and guidance	Specifications provide guidelines for construction including omission/modification locations, test section lengths (300 or 600 feet), chemical application, initial and final mixing, compaction, curing and protection, and restabilization

Categories	Notes
Field quality control and assurance	Field quality control includes measurement of stabilized thickness, lime content for lime stabilized subgrades, field density, and field CBR for cement stabilized layers Field CBR is measured using the DCP
Measurement and payment	Measurement and payment are based on the per square yard construction of a chemically stabilized subgrade and the cost of stabilizer (lime, FA, LKD, CKD, cement) in tons

Table 3.3. shows current MDOT recommendations for including stabilized subgrade layer properties in pavement design procedures.

Table 3.3. Michigan Department of Transportation Recommendations for Pavement Design Inputs when Using Stabilized Subgrade.

Pavement Design Method	Pavement Design Input
Guide for Design of Pavement Structures (American Association of State Highway and Transportation Officials, 1993)	Use a 1.36 multiplier for the existing subgrade
AASHTOWare Pavement ME Design software	Use a new subgrade layer above the existing subgrade with a subgrade M_R four times the M_R of the existing subgrade; this layer should match the thickness of the anticipated stabilization depth

3.2 Review of Other States' Subgrade Stabilization Specifications and Pavement Design Inputs

A comprehensive review of subgrade stabilization specifications and pavement design inputs from other states, as well as from the Federal Highway Administration, Federal Aviation Administration, U.S. Army Corps of Engineers, and U.S. Air Force was conducted.

Among all surveyed states, 58 percent (29 states) have subgrade stabilization in their standard specifications for construction or use subgrade stabilization with special provisions; 12 percent (6 states) have researched the use of subgrade stabilization in road construction; and 30 percent (15 states) do not have any information related to the use of subgrade stabilization in road construction in their standard specifications.

Comparative analyses regarding the types of stabilizers used, mix design procedures, construction acceptance procedures, and pavement design inputs were conducted. Table 3.4 summarizes the results of these analyses, comparing MDOT's subgrade stabilization specifications and practices to the specifications and practices from other states.

Table 3.4. Comparison of Subgrade Stabilization Specifications and Practices.

Categories	Michigan	Other States
Stabilizing material	Cement, lime (quicklime and hydrated lime), lime-fly ash	Most states use cement, lime, and lime-fly ash; exceptions include the following: Class C fly ash (Colorado, Texas, Indiana, Alaska, Illinois, Iowa, Kansas, Missouri, Nebraska, Oklahoma, Wisconsin) Crushed stone (Kansas) Emulsified asphalt (Kansas, Tennessee) Geotextile (Mississippi, Virginia) Cement kiln dust (Nebraska, Oklahoma)
Selection process for soil modification/ stabilization	Regional soil engineer recommends subgrade stabilization based on preliminary soil investigations	Specified in: Pavement design manual (Arizona, Colorado) Geotechnical manual (Ohio, Indiana, Illinois) Treatment guidelines for soils and bases in pavement structures (Texas, Alaska) Standard specification for construction (Tennessee)
Mix design criteria	Contractor-designed soil mix with cement, lime, or a lime-fly ash combination	Contractor-designed mix design (Arizona, Colorado, Florida) State protocol for mix design (Ohio, Texas, Indiana, Alabama, Alaska, Arkansas, Illinois, Oklahoma, Tennessee, Wisconsin)
Water criteria for mixing/ curing	If nonpotable water is used, follow the requirements in the standard specification for construction	A pH of 6.0–8.5 or potable water without testing (Arizona) Free of industrial wastes and other objectionable matter (Texas) Potable water without testing (Iowa, Missouri)
Required laboratory tests	Soil classification for untreated and treated soils per AASHTO M 145-91 (American Association of State Highway and Transportation Officials, 2021) and ASTM D2487-17e1 (ASTM International, 2020) Moisture-density tests for untreated and treated soils per AASHTO T 99-22 (American Association of State Highway and Transportation Officials, 2022) California bearing ratio lab tests for treated uncured soils per ASTM D1883-21 (ASTM International, 2021) Liquid limit and plastic limit tests per ASTM D4318-17 (ASTM International, 2018b)	Most states require similar laboratory tests; exceptions include the following: Lime treated soil: pH, PI, swell potential, UCS after 5 days of curing at 100°F in sealed airtight conditions (Arizona) Organic content based on loss on ignition, sulfate content based on colorimetric method, pH for lime stabilized soils, and expansion testing for treated soils (Ohio) Two M_R tests in chemically stabilized soils (Indiana) Durability, flexural beam, splitting tensile, and UCS tests for cement; Atterberg limits in accordance with AASHTO test methods, optimum water content, and compacted density tests with a Poisson's ratio of 0.20–0.45 (0.20 for bound, 0.45 for unbound) for asphalt (Alaska) California bearing ratio, M_R, and UCS tests; CBR tests and M_R tests on fly-ash stabilized subgrade and subgrade soils are conducted in accordance with ASTM D1883-21 (ASTM International, 2021) and AASHTO T 292 (American Association of State Highway and Transportation Officials, 1997), respectively (Wisconsin)

Categories	Michigan	Other States
	Eades and Grim pH test for minimum lime or LKD content determination per ASTM D6276-19 (ASTM International, 2019b) Unconfined compressive strength tests for treated and cured soils per ASTM D5102-96, ASTM D1633-17, ASTM D2166-06, and ASTM D3551-17 (ASTM International, 2017b, 2018a, 2010, 2017a)	
Subgrade preparation	Shape existing material to conform to lines and grades shown on the plans Remove all deleterious material (topsoil, roots, organic materials, foreign debris, rock fragments larger than 2½ inches, etc.) Dispose of deleterious materials in accordance with standard specifications	Most specifications include the following tasks: shape existing material to conform to typical sections shown on the plans; remove all deleterious material, organic materials, and particles retained on a 3-inch sieve; bring subgrade to a compacted condition, true line, and grade; scarify, pulverize, and mix the material with water; and compact, finish, and cure the stabilizer in lengths permitting the full roadway width to be complete Exceptions include the following: Proof roll and remove unsuitable materials by over-excavating (Colorado, Texas) When cement stabilization of foundation soils is required in a cut or at-grade section, the top 12 inches of soil shall be removed and stockpiled prior to constructing the 14-inch thick cement stabilization and replaced when the cement stabilization is complete; when cement stabilization is required in a fill section, it shall be constructed prior to placement of the 12 inches of soil for cement stabilized subgrade soil (Indiana) Where the depth of lime stabilization exceeds 6 inches (150 mm), the excess subgrade soil shall be removed, placed in windrows, and processed as an additional lift (New York) When lime treatment depth is more than the contractor's equipment is capable of handling, excavate material above the bottom layer to be treated in excess of what the contractor's equipment can treat, and place it in a windrow or stockpile (Wyoming)
Drainage	Special provisions require adequate drainage during the entire construction period to prevent water from collecting or standing on the area to be stabilized, pulverized, mixed, or partially stabilized No mention of long-term drainage was made in any SP	Most specifications do not provide guidance for drainage; exceptions include the following: Sufficient drainage is required at all times to prevent water from pooling on the subgrade (Indiana) The subgrade shall be kept drained during the construction of the pavement structure; if earth berms are deposited along the edge of the subgrade, a provision shall be made for surface drainage by cutting lateral ditches through the berms; drainage construction work shall consist of constructing pipe drains and pipe underdrains of the required inside diameter and constructing French drains consisting of trenches filled with aggregate (Illinois) Provide and maintain ditches and drains to drain the subgrade satisfactorily (North Carolina) The contractor shall provide effective drainage for the subgrade and maintain it in a satisfactory condition until the next course is placed (Virginia) Cut drains through the shoulders adjacent to the excavated areas to drain the roadbed; cut drains through the windrows at sufficient intervals to prevent ponding of water; move the windrows when necessary to allow the subgrade to dry (Wyoming)

Categories	Michigan	Other States
Depth	Most often 12 inches, one project had an 8-inch depth	Most specifications define the required depth as "according to the plans;" exceptions include the following: At least 12 inches; if the stabilized thickness is more than 12 inches, two equal lifts should be used (Arizona) At least 14 inches for mixing depth and 12 inches for cement stabilized subgrade (Indiana) At least 8 inches for cement and lime stabilized subgrades (Kentucky) At least 8 inches compacted for lime stabilized subgrade (North Carolina) At least 6 inches (North Dakota) At least 10 inches (Wyoming)
Weather/ seasonal considerations	Ambient temperature of 40°F and rising, with seasonal limitation between April 1st and October 31st	Ambient temperature >40°F (Arizona) Lime and soil temperature >35°F (Colorado) Lime and soil temperature >40°F; do not spread the stabilizer on frozen subgrade (Ohio) Start treatment operations only when air temperature is >35°F and rising or is at least 40°F (Texas) Soil temperature >45°F measured 4 inches below the surface and with air temperature rising; the chemical modifier shall not be mixed with frozen soils or with soil containing frost; chemical soil modification shall only be performed in areas that are going to be paved during the same construction season (Indiana) Lime temperature >40°F and rising; modification is allowed in colder temperatures; hydrated lime should not be applied on frozen ground (Alaska) Application of lime will not be permitted when the surface temperature is <50°F (10°C), nor shall it be applied before April 1 or subsequent to a date in October sufficiently early to give reasonable assurance that all mixing, spreading, and rolling will be complete on or before October 31, except by written permission of the engineer (Arkansas) Apply lime at ground temperatures above 35°F; do not apply lime if the ground temperature is expected to drop below 35°F before mixing and compacting is complete; apply cement at air temperatures above 40°F and rising; do not apply cement to frozen basement material (California) The engineer shall have the authority to suspend work when unsuitable severe weather conditions or other conditions at the site make for circumstances beyond the contractor's control, which are unfavorable for the satisfactory performance of the work, and when the contractor does not comply with the contract or orders of the engineer (Illinois) The cement treated subgrade shall not be mixed while the atmospheric temperature is below 40°F or when conditions indicate that temperatures may fall below 40°F within 24 hours or when it is foggy, rainy, or the soil or subgrade is frozen (Iowa) Do not perform lime treatment operations if the ambient air temperature is below 40°F or the soil is frozen (Kansas) The soil-fly ash mixture shall not be mixed while the atmospheric temperature is below 40°F or when conditions indicate that temperatures may fall below 40°F within 24 hours or when it is foggy, rainy, or the soil or subgrade is frozen (Missouri)

Categories	Michigan	Other States
		Lime stabilization of the subgrade shall not be done when the subgrade temperature is below 5°C, nor in the period from October 15 to May 15, except by written permission of and under such special limitations as set forth by the deputy chief engineer (Technical Services); the hydrated lime shall not be mixed with frozen subgrade soil or when the subgrade contains frost; lime shall not be applied when wind conditions, as determined by the engineer, are such that blowing lime becomes objectionable or hazardous to traffic, workers, and adjacent property owners (New York) Do not perform lime stabilization when the air temperature is below 45°F; do not mix the lime with frozen soils or when the soils contain frost; do not construct lime treated soil that will not be covered with a layer of pavement or base by December 25 of that same calendar year (North Carolina) Apply additives for subgrade stabilization when the air temperature is at least 40°F (4°C) and rising; apply additives for subgrade modification when the air temperature is at least 33°F (1°C) and rising; measure the air temperature at a location 4 feet (1.2 meters) above the ground in the shade and away from artificial heat; do not apply additives if the ground is frozen; protect the quality of the additive and treated subgrade from the weather (Oklahoma) The spreading and mixing of fly ash with the subgrade is delayed 24 hours after heavy rains to avoid construction on wet ground (Wisconsin) Perform lime stabilization when the air temperature is 45°F (10°C) or above; do not mix the lime with frozen soils or soils containing frost; do not apply lime when wind conditions are such that excessive loss of lime occurs or when blowing lime becomes hazardous to traffic, workers, or adjacent property owners (Wyoming)
Application and mixing	Application: Apply contractor-designed chemical in dry weight basis on scarified subgrade Conduct application rate verification testing and submit results to the engineer Do not apply when wind conditions create potentially hazardous conditions Mixing: Mixing has two stages: initial and final Lime or lime-fly ash: Add water to raise moisture levels 5% above the optimum moisture content and mix until required gradation is achieved Complete initial mixing within 4 hours of chemical application Lime or lime/fly ash materials may require 24 hours or more mellowing time prior to final mixing	Most specifications are similar to Michigan's specifications; exceptions include the following: When the design requires treatment to a depth >12 inches, treat the subgrade soil in equal layers; remove and stockpile the top layer, then treat the lower layer and allow to cure in place; after final mixing, compact the lower layer in maximum 12-inch thick compacted lifts; then, treat, mix, and compact the stockpiled lifts (Arizona) Prior to full-scale production, a test section of at least 100 feet needs to be constructed; specification has details on application, initial mixing, and final mixing (Colorado) Begin mixing lime within 6 hours of application; allow 1–4 days of mellowing (longer mellowing is required when sulfates are present); apply fly ash only when mixing and compaction can be completed the same working day (Texas) For Portland cement modified soils, mixing shall be completed within 1 hour of Portland cement placement and grading and final compaction shall be completed within 3 hours after mixing; fly ash modified soils shall be compacted within 4 hours; lime modified soils shall be compacted within 24 hours (Indiana) During mixing operations, measure and record the ground temperature at full mixing depth; take a composite sample from 5 random locations after initial mixing (California) Cement shall be spread only on areas where the mixing and compaction operations can be completed within 2 hours (Iowa)

Categories	Michigan	Other States
	After mellowing, remix soil as final mixing with added water Complete final mixing within 5 days of initial mixing Cement: Do not add water for initial mixing Mix until the required gradation is achieved For the final mixing, add water to at least optimum moisture content Add water to the soil-cement mixture within 2 hours after the initial mixing	Fly ash shall be spread only on areas where the complete placement operation can be completed within 2 hours (Missouri)
Compaction	Compact to at least 95% of the maximum dry density unit weight established for the stabilized layer	Most specifications require compaction to 95% of the MDD; exceptions include the following: Compact to 98% of the MDD (Ohio) Compact the CSS to at least 97% relative compaction (California, North Carolina) The subgrade shall have an MDD of 95% of the standard laboratory dry density and a minimum immediate bearing value of 8.0 (Illinois) After the contractor has thoroughly mixed the soil binder with the subgrade sand, the upper 6 inches (150 mm) of the subgrade shall be compacted to the optimal stiffness, as defined by a deflection target value established by the engineer (Nebraska)
Curing	Immediately after the stabilized subgrade has been compacted and finished, surface must be protected against rapid drying for 7 days by periodic sprinkling Subgrade must be kept moist for the full 7-day curing period unless covered by subsequent layers of subbase or aggregate base	Most specifications require a moist cure for 7 days; exceptions include the following: A curing seal or loose aggregate lift can be used to maintain moisture (Arizona, Colorado, Indiana, Alabama, Tennessee) At the end of each day's operation, cover the stabilized work area's surface with a curing coat for curing the chemically stabilized subgrade; if the surface dries before applying a curing coat, apply water for temporary curing (Ohio) For lime, maintain moisture during curing by sprinkling or asphalt membrane; cure untreated materials with a PI ≤35 for 2 days, and cure untreated materials with a PI >35 for 5 days; for fly ash, maintain a thorough and continuous moist condition by sprinkling; cure the finished section for 7 days for type FS and at least 24 hours for type CS; for cement, cure at least 3 days by sprinkling or asphalt membrane (Texas) For cement or fly ash, the surface shall be protected against rapid drying and maintained in a thorough and continuously moist condition by sprinkling for a period of not less than 3 days or until the pavement section is placed (Iowa) Protect the finished subgrade from drying by spraying with water to maintain a continuous moist condition; the contractor may apply an asphalt prime coat instead of keeping the finished surface moist with water during the curing period (Kansas)

Categories	Michigan	Other States
		After the fly ash treated course has been finished, the surface shall be protected against rapid drying by either maintaining a thorough and continuously moist condition by sprinkling or applying a 2-inch layer of earth on the completed course and maintaining it in a moist condition for a period of not less than 3 days or until the pavement section is placed (Missouri) Following primary mixing operations, the stabilized course shall be allowed to cure for at least 24 hours plus any additional time required for the lime to properly react with the subgrade soil (New York, Wyoming) Following primary mixing operations, cure the stabilized layer for 1–4 days (North Carolina)
Pavement design input	*Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials, 1993): Use a 1.36 multiplier for existing subgrade AASHTOWare Pavement ME Design software: Use a new subgrade layer above the existing subgrade with a subgrade M_R four times the M_R of the existing subgrade.	Use chart in *Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials, 1993) to determine layer coefficients for cement or lime stabilized subgrades; if the UCS is >800 psi, the layer coefficient is 0.23 (Arizona) Soil-cement subgrade M_R=50,000–1,000,000 psi (typically 500,000 psi), lime stabilized subgrade M_R=30,000–60,000 psi (typically 45,000 psi), lime-cement-fly ash stabilized subgrade M_R=500,000–2,000,000 psi (typically 1,500,000 psi) (Colorado) When stabilization is used in an entire area (global stabilization), the increased M_R is calculated using a 1.36 multiplier for the native subgrade M_R (Ohio) Lime or cement treated subgrade M_R=30–45 ksi; when a subgrade will be treated to provide a working platform for construction equipment, do not include the treated subgrade in the structural design (Texas) The M_R of the stabilized subgrade layer is specified in the geotechnical report (Indiana) Users running AASHTOWare Pavement ME Design software should use the inputs provided in Appendix F of the Input Guide (Kentucky)
Construction quality control/ acceptance	Field quality control includes the measurement of stabilized thickness, lime content for lime stabilized subgrades, field density, and field CBR for cement stabilized layers Field CBR is measured using the DCP	Most specifications required depth tests, stabilizer percentages, and density tests for construction quality control and acceptance; exceptions include the following: Proof rolling, density, and field verification of mix design using field samples obtained from random locations for every 15,000 cubic yards (Ohio) Depth of treatment, density, and proof rolling as an indicator for sufficient curing (Texas) Acceptance testing for compaction of cement stabilized subgrade soils is performed on the finished grade using a light weight deflectometer (LWD) at 2,000 square yard intervals in accordance with 203.24(b); acceptance testing will begin 7 days after compaction; average and individual deflection values should not exceed 0.14 mm and 0.17 mm, respectively (Indiana)
Measurement and payment	Measurement and payment are based on the per square yard construction of a chemically stabilized subgrade and the cost of stabilizer (lime, fly ash, LKD, CKD, cement) in tons	Most specifications measure the stabilized subgrade in square yards and the chemical in tons; exceptions include the following: Square yards and inches deep of cement or lime stabilized subgrade, tons of cement or lime, square yards of curing coat, hours of test rolling, lump sum mixture design for chemically stabilized soils (Ohio) Soil binder is paid per cubic yard, subgrade stabilization is paid per 100 feet (100 meter) station units, and water is paid per 1,000 gallons (Nebraska)

CHAPTER 4 SURVEY OF STATE DEPARTMENT OF TRANSPORTATION PERSONNEL

This task was conducted as two subtasks: interview and gather lessons learned from MDOT personnel (Task 3a), and interview and gather lessons learned from other state department of transportation (DOT) personnel (Task 3b). Prior to conducting interviews, the research team developed and deployed an online questionnaire to collect information on previous subgrade stabilization projects. Survey responses are detailed below.

4.1 Subgrade Stabilization Survey of MDOT Personnel

The research team developed a survey to gather information on MDOT subgrade stabilization projects. After soliciting the contact details of the respondent and the project numbers and locations of past subgrade stabilization projects, the following questions were posed:

- How was the stabilizer type and rate selected?
  - Specified in the construction specification.
  - Contractor designed.
  - Other (please specify).
- Is a mix design summary available? If yes, please provide a copy of the mix design summary.
- What went well and what concerns existed during construction?
- Were there any issues with the additional testing burden required when developing a mix design and constructing, inspecting, and accepting a stabilized subgrade layer? If yes, please describe.

Finally, respondents were asked to share any lessons learned and other details not related to the above questions. A copy of the survey is included in Appendix A of this report. A summary of survey responses from MDOT personnel is provided below.

4.1.1 Survey Respondents

Six survey responses were received from MDOT personnel.

4.1.2 Project Numbers and Locations of Past MDOT Subgrade Stabilization Projects

Table 4.1 summarizes the responses received regarding past MDOT subgrade stabilization projects.

Table 4.1. Project Numbers and Locations of Past MDOT Subgrade Stabilization Projects.

Project Number	Project Description	Responses Received
115799	I-69 from Ballenger Rd. to Fenton Rd., Genesee County	1
117992	US-131 from 10 Mile Rd. to 14 Mile Rd., Kent County	2
52803	I-96 from Schaefer Rd. to M-39, Wayne County	2
37795	I-75/I-96 Interchange, Wayne County	2
201437	I-75 13 Mile Rd. to Square Lake Rd., Oakland County	1
48271	M-84, Bay and Saginaw County	1

4.1.3 Selection Methods for Stabilizer Type and Rate

Figure 4.1 shows the most commonly reported selection methods (i.e., specified in the construction specification, contractor designed, or other) for stabilizer type and rate.

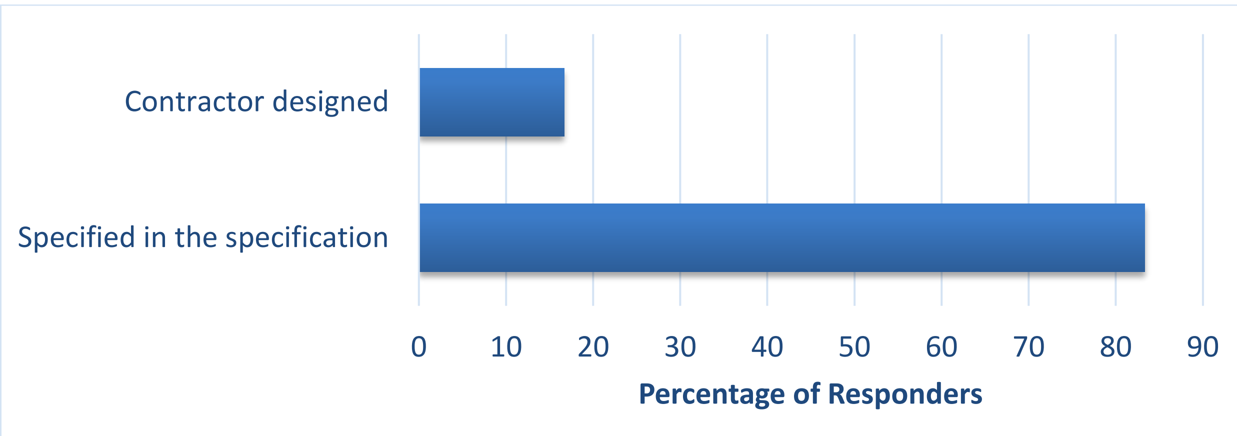

Figure 4.1. Selection Methods for Stabilizer Type and Rate.

4.1.4 Availability of a Mix Design Summary

Figure 4.2 shows the reported availability of a mix design summary. Respondents provided copies of a mix design summary (*I-69 Subgrade Stabilization* [Job No. 115799]) from Flint, Michigan, and a construction specification (*Chemical Stabilized Subgrade* [Job No. 117992]).

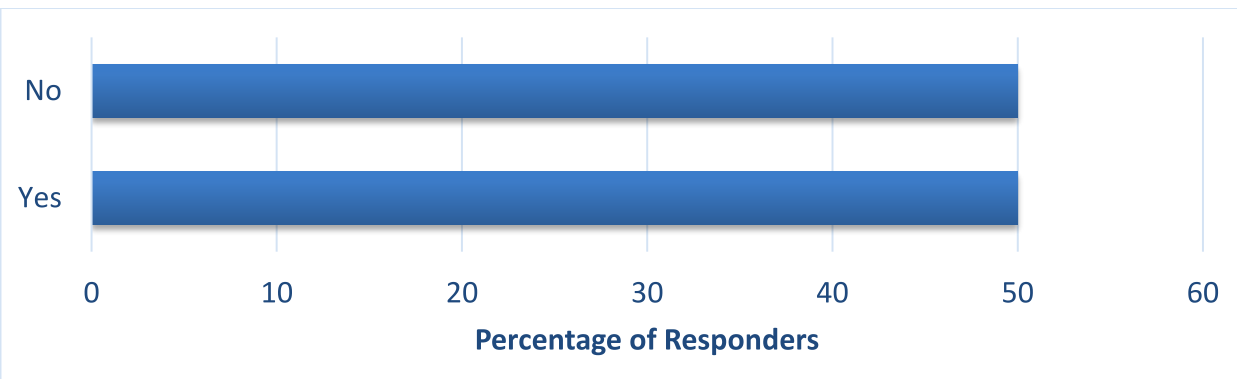

Figure 4.2. Availability of a Mix Design Summary.

4.1.5 Successes and Concerns During Construction

The respondents provided the following information related to their experiences:

- "The overall project outcome was good. Some concerns or issues were the fact that we were essentially building a bathtub, constricting the bottom with cementitious material and sides with impermeable clay. One other issue was the treatment extended beyond the footprint of the road, so driving guardrail posts or signs was difficult. We also had issues with the stabilizer machine taking the tops of pipes and then having to fix them, we had some shallow pipes."
- "Inexperience with this process was really the only concern. Overall, it turned out well and seems like it would be a great option in applicable situations. This project stabilized an area of good sand, but in areas of clays or other types of unstable soils, this would be very useful."
- "MDOT required a contractor soil sampling plan for approval. The placement went well and smooth, and coordination with the contractor went well. Additional training was required for operating the testing equipment for the stabilized subgrade application."
- "The end products of all 3 projects were very satisfactory. There was Contractor strife associated with the I-96 project and a subsequent project (M-53) in which stabilization was pulled. The 2020 I-75 project was Design-Build and the Contractor elected to use stabilization."
- "There were pockets of sand subgrade which created challenges in the field during the Contractor's stabilization operations."
- "Lime stabilization worked well to stiffen soft and plastic clay loam subgrade so that a road foundation could be built."

4.1.6 Additional Testing Burden when Developing a Mix Design and Constructing, Inspecting, and Accepting a Stabilized Subgrade Layer

The respondents provided the following information related to their experiences:

- "None. Testing had to be planned and was additional work, but it was all part of the contract."
- "No, there were some issues about covering the stabilized subbase with sand too soon, but ultimately, we approved that to keep the moisture content where it was needed."
- "There were additional testing requirements, and additional equipment specified in the SP for testing and the Inspection and Testing Staff had to be trained and coordinated with the MDOT Geotech unit to make sure all procedures were being followed appropriately."

- "Mix designs were assigned to the Contractor. The submittals and approvals did not go smoothly. Again, this mostly had to do with the strife of the Contractor. DCP verification of stabilized subgrade is an extra step and burden on staff."

4.1.7 Lessons Learned and Other Details

The respondents provided the following lessons learned related to their experiences:

- "Make sure pipes are deep enough so they are not impacted."
- "The project was a success. However, I do not think the existing subgrade of sand was an ideal candidate for this type of subgrade (stabilization) because the underlying soil conditions were good. This type of application would be more beneficial for clay or poor underlying soil conditions. Refer to Special Provisions 12DS105(N445) and 12DS301(N370) and 12CF303(A225)"
- "Our Michigan Contracting community has not partnered well with MDOT in trying to introduce this proven method."
- "There were no lessons learned by MDOT. The only lesson I recall is that the Contractor learned how to be more efficient in the field operations. Hope to know if the subgrade is performing as intended though I am not aware of any study to show those benefits."

4.2 Subgrade Stabilization Survey of Other State DOT Personnel

4.2.1 Survey Respondents

A similar survey on subgrade stabilization for roadway construction was developed and deployed to other state DOT personnel. Completed surveys were received from 31 respondents in 28 states. Figure 4.3 shows the responding states.

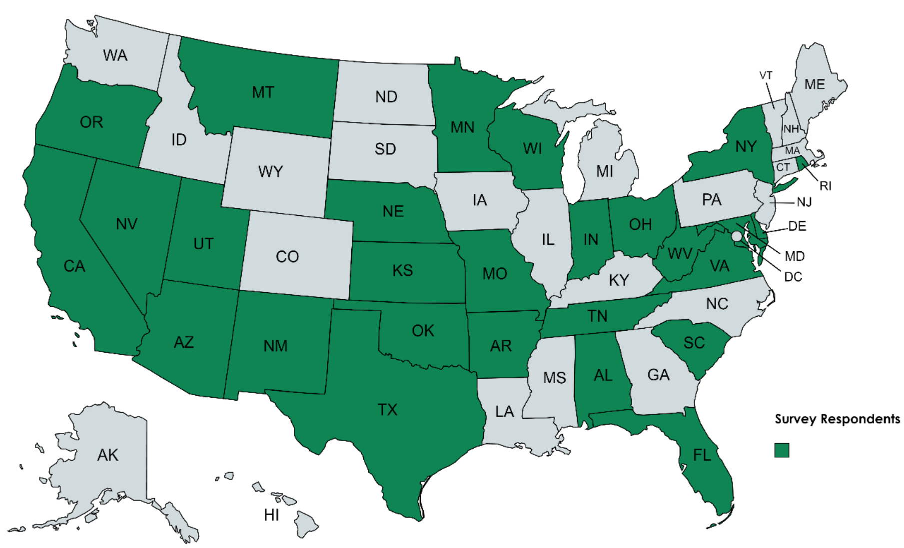

Figure 4.3. Survey Respondents from Other State DOTs.

4.2.2 Project Numbers and Locations of Past Subgrade Stabilization Projects in Other States

The respondents provided project locations and project numbers for past stabilization projects in other states.

4.2.3 Agency Experience with Subgrade Stabilization

Figure 4.5 shows each agency's relative experience with subgrade stabilization in terms of the number of projects completed.

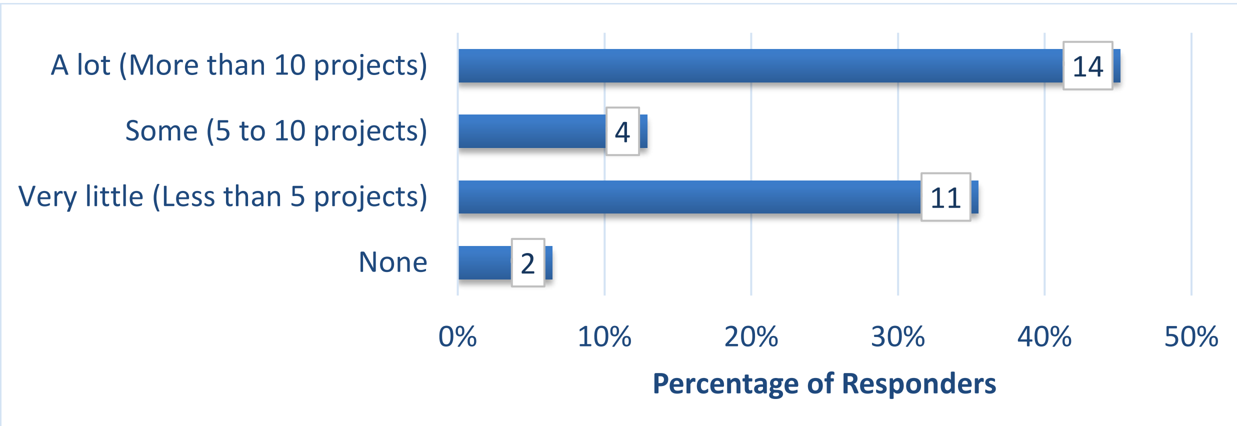

Figure 4.5. Agency Experience with Subgrade Stabilization.

4.2.4 Treatment Materials Used for Subgrade Stabilization/Modification

Figure 4.6 shows the various treatment materials commonly used for subgrade stabilization and modification. Table 4.2 details additional types of treatment materials used in other states.

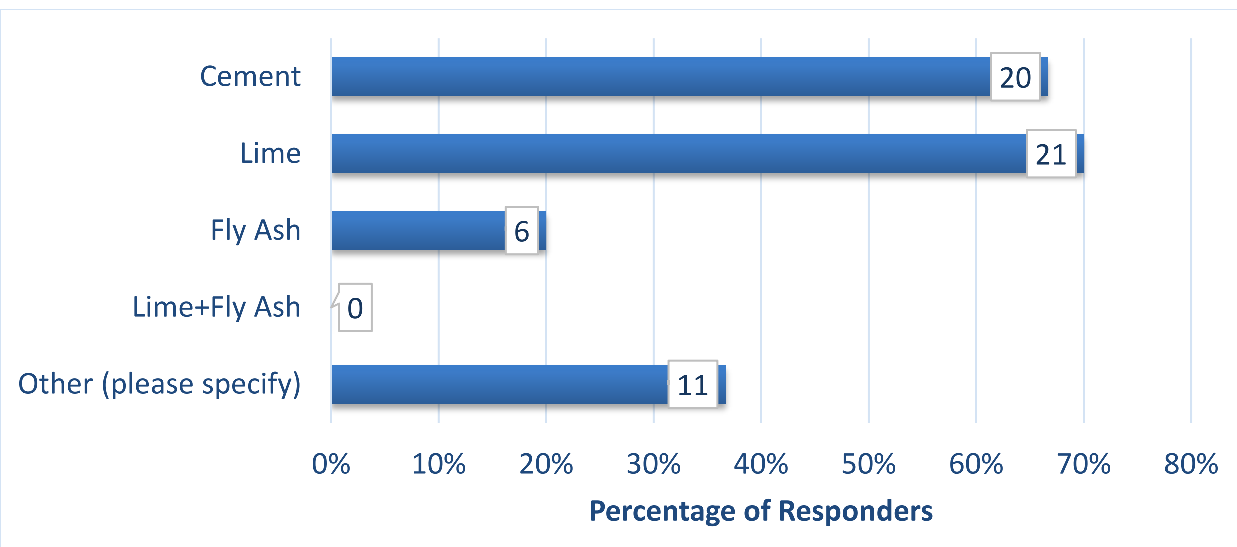

Figure 4.6 Treatment Materials Used for Subgrade Stabilization/Modification.

Table 4.2. Other Treatment Materials Used for Subgrade Stabilization/Modification.

Other Treatment Material	Number of States Indicating Use
Aggregate, rock/stone embankments	2
Geotextile/geogrid	4
Geosynthetics with granular materials	2
Over excavation and replacement	1
Cement kiln dust	1
B borrow and No. 10 sieve screening materials	1

4.2.5 Project Selection Methods for Subgrade Stabilization

Based on the survey responses, approximately 20 percent of responding states (6 states) select projects for stabilization based on standard specifications, and approximately 30 percent of the states (9 states) select projects based on standard operating procedures. A few states use both for project selection. The remaining states (19 states) use other methods to select projects, as indicated in Table 4.3.

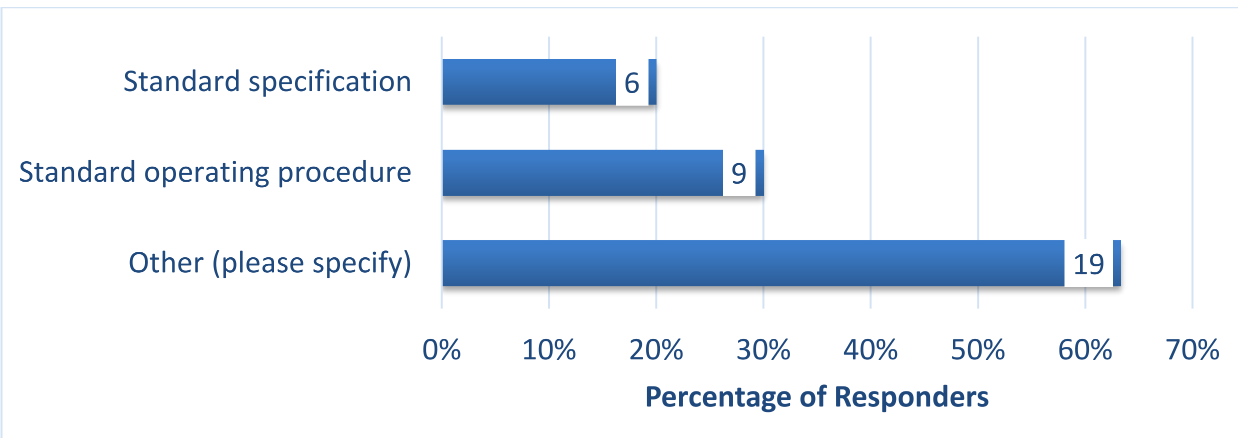

Figure 4.7. Project Selection Methods for Subgrade Stabilization.

Table 4.3. Other Project Selection Methods.

State	Project Selection Method
Ohio	Ohio DOT's Geotechnical Bulletin 1 for *Plan Subgrades* (Ohio Department of Transportation, 2021) explains process for determining stabilization; for all multilane, divided projects over one mile and any roadway where more than 30% of the subgrade requires treatment, global chemical stabilization is used
Arizona	Project-specific conditions
Nebraska	Expected plasticity index
Arkansas	Special provision is included in projects as an "if and where directed item" based on anticipated soil conditions
Missouri	Not normally specified during design development; required infrequently but when needed, it is "change ordered" into a contract due to differing site conditions
South Carolina	Based on the design; if not designed, then the contractor's option
New Mexico	Based on soil data
Wisconsin	Generally used to solve construction issues, so not included in plan documents, but have been included in the design for a few projects

State	Project Selection Method
New York	Typically only utilized if construction problems are encountered
Utah	Based on field investigation during the pavement design
Indiana	Geotechnical Division based on project size, groundwater
Virginia	Case by case based on the site and subgrade condition
Rhode Island	Field evaluation for candidacy
Tennessee	As needed
Alabama	In situ conditions dictate

4.2.6 Use of Cost-Benefit Analysis for Project Selection

Only 13 percent of the responding states (4 states) use cost-benefit analysis for project selection (Figure 4.8). The remaining 87 percent (26 states) do not use cost-benefit analysis for project selection.

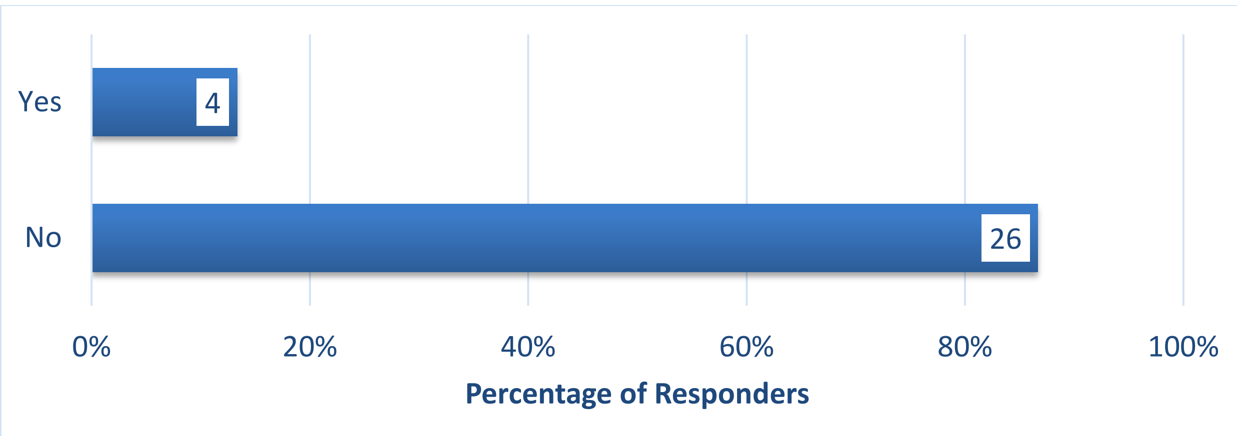

Figure 4.8. Use of Cost-Benefit Analysis for Project Selection.

When asked to provide additional information about how cost-benefit analysis is used for project selection, 5 states provided additional responses, as detailed in Table 4.4.

Table 4.4. Cost-Benefit Analysis Used for Project Selection.

State	Cost-Benefit Analysis Use
Texas	Stabilizer selection is driven by the soil properties; the stabilizer type and percent are selected based on mix design; cost should not drive the option
California	Stabilized subgrade used in pavement structural sections and compared with other alternatives
Arkansas	Resident engineer does a calculation of the cost of soil stabilization for selected areas versus the cost of undercut and backfill using the bid prices for the items in the contract
Indiana	Look for various subgrade types in standard specification and recommend cost-effective
Montana	A formal cost-benefit is typically not completed; the initial costs of a pavement section that is *stabilized* is compare to one that is not, but this comparison is complicated because the stabilization is often part of a construction platform

4.2.7 Main Goals of the Subgrade Treatment

Approximately 57 percent of responding states (17 states) use subgrade treatment for long-term stabilization, 23 percent (7 states) use it for construction platform modification, and 20 percent (6 states) use it for both (Figure 4.9). Table 4.5 lists additional remarks from survey respondents.

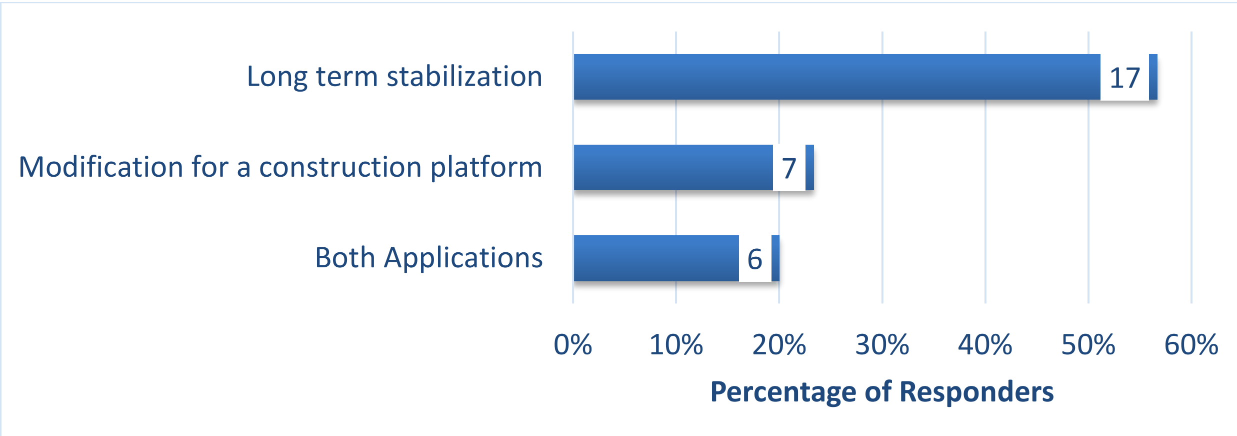

Figure 4.9. Main Goals of the Subgrade Treatment.

Table 4.5. Other Goals of the Subgrade Treatment.

State	Other Subgrade Treatment Goals
Texas	Both applications
Nebraska	Both long-term and modification for a work platform
New York	Both long-term stabilization and modification for a construction platform
Indiana	Construction platform and provide subgrade durability during the service life
Montana	Used for both long-term stabilizations (pavement design) and as a construction platform
Alabama	Depends on the in situ conditions

4.2.8 Availability of Mix Design Specifications for Subgrade Stabilization

Approximately 41 percent of responding states (12 states) have mix design specifications, and 59 percent (17 states) do not have any specifications for mix design (Figure 4.10).

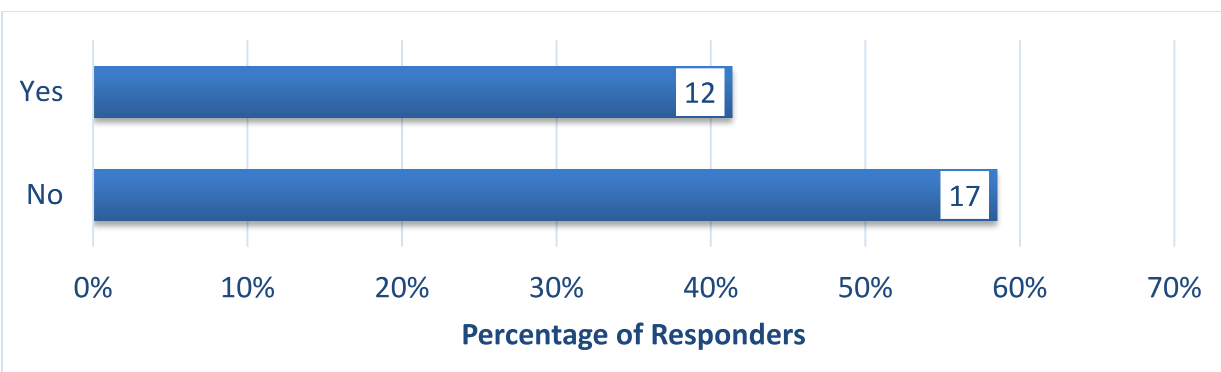

Figure 4.10. Availability of Mix Design Specifications.

Among the states indicating available mix design specifications, 7 states provided them to the research team. These states included California, Indiana, Maryland, Minnesota, Oklahoma, Tennessee, and Virginia. Table 4.6 summarizes these mix design specifications.

Table 4.6. Summary of Mix Design Specifications.

<table>
<tr><th>State</th><th>Mix Design Specifications</th></tr>
<tr><td>California</td><td>Mix designs are performed by the state for lime and cement as described in Section 24 of Standard Specifications for Construction (California Department of Transportation, 2018). For lime stabilized soils, the engineer determines the final application rate for each lime product proposed from the samples submitted based on California Test 373.2. For cement stabilized soils, the engineer determines the final application rate based on ASTM D1633, Method A (ASTM International, 2018a).</td></tr>
<tr><td>Indiana</td><td>The mix design procedure is given in the Design Procedures for Soil Modification or Stabilization developed by the Indiana DOT’s Geotechnical Division (Indiana Department of Transportation, 2021a). These guidelines describe design procedures for mechanical and chemical modification/stabilization, laboratory test requirements, and construction considerations. The following criteria are included in this guide for selecting the type of chemical for stabilization and modification:
1. Chemical selection for stabilization.
a. Quicklime or hydrated lime: Clay content >30% and PI >20. The lime shall have a soluble sulfate content of <5%. Quick lime should be used in a slurry mixture.
b. Cement: Clay content <30% and PI ≤20.
2. Chemical selection for modification.
a. Lime or Class C fly ash: Clay content >30% and PI >20.
b. Cement: Clay content ≤30% and PI ≤20.
The recommended quantities of chemicals are as follows:
<table>
<tr><th>Chemical</th><th>Chemical Modification</th><th>Chemical Stabilization</th></tr>
<tr><td>Quicklime or hydrated lime</td><td>5–7%</td><td>5–7%</td></tr>
<tr><td>Lime byproduct</td><td>6–7%</td><td>Not recommended</td></tr>
<tr><td>Cement</td><td>5–8%</td><td>5–8%</td></tr>
<tr><td>Fly ash</td><td>12–15%</td><td>Not recommended</td></tr>
</table>
The minimum strength gains required for chemical modification and the target design strength for stabilization are as follows:
<table>
<tr><th>Chemical</th><th>Chemical Modification</th><th>Chemical Stabilization</th></tr>
<tr><td>Quicklime or hydrated lime</td><td>50 psi</td><td>150 psi</td></tr>
<tr><td>Lime byproduct</td><td>50 psi</td><td>Not recommended</td></tr>
<tr><td>Cement</td><td>100 psi</td><td>300 psi</td></tr>
<tr><td>Fly ash</td><td>50 psi</td><td>Not recommended</td></tr>
</table></td></tr>
<tr><td>Maryland</td><td>Mix design procedures for the cement treated base/subgrade are described in the Standard Specifications for Construction and Materials (Maryland Department of Transportation, 2022). Section 502.03.04 of the specification states the contractor shall submit a mix design report along with soil and Portland cement samples at least 45 days prior to the start of construction for review and approval. Design recommendations shall clearly show the following for each mix design: optimum moisture content, maximum dry density, and the proper rate of application for Portland cement necessary to achieve the 7-day compressive strengths of 450–700 psi for cement treated base and 100–300 psi for cement modified subgrade or other ranges determined by the Office of Materials Technology.</td></tr>
</table>

<table>
<tr><th>State</th><th>Mix Design Specifications</th></tr>
<tr><td>Minnesota</td><td>
The Minnesota Department of Transportation Grading and Base Manual (Minnesota Department of Transportation, 2021) includes a soil-cement laboratory design procedure. This procedure includes the following lab tests: gradation, liquid limit, plastic limit, AASHTO and Minnesota DOT soil classifications, organic content, soil pH, and soil-cement mixture moisture-density relationships using the following estimated cement contents:
<table>
<tr><th>AASHTO Classification</th><th>Cement by Mass</th><th>Cement for Wet-Dry/ Freeze-Thaw Tests</th></tr>
<tr><td>A-4, A-5, A-6, A-7</td><td>6%</td><td>4, 6, 8%</td></tr>
</table>
Using these cement contents, the soil-cement loss percentage is determined according to Method A in AASHTO T 135 and T 136 (American Association of State Highway and Transportation Officials, 2013b, 2013a). The maximum allowable soil-cement loss percentages are as follows:
<table>
<tr><th>AASHTO Classification</th><th>Maximum Allowable Soil-Cement Loss</th></tr>
<tr><td>A-4 or A-5</td><td>10%</td></tr>
<tr><td>A-6 or A-7</td><td>7%</td></tr>
</table>
The final step of the mix design is to conduct UCS tests according to AASHTO T 22 (American Association of State Highway and Transportation Officials, 2017). Specimens are compacted to the maximum dry density, moist cured for 7 days, and soaked for 4 hours. The 7-day compressive strength (with no correction for the length-to-diameter ratio) must range from 200 to 350 psi.
Section 5-692.521 of the manual provides guidelines for the addition of lime (quicklime or hydrated lime) to dry soil with a maximum percentage of 2 percent.
</td></tr>
<tr><td>Oklahoma</td><td>
The OHD L-50 Soil Stabilization Mix Design Procedure (Oklahoma Department of Transportation, 2021) provides guidelines for soil stabilization using fly ash, cement kiln dust, Portland cement, and lime. Two methods are described: an abbreviated procedure based on tabular data and a full mix design procedure. The full mix design procedure is preferred for stabilization. The abbreviated method uses the following tabular data:
<table>
<tr><th colspan="13">SOIL STABILIZATION TABLE</th></tr>
<tr><th rowspan="3">ADDITIVE (Expressed as a percentage added on oven-dry basis)</th><th colspan="12">SOIL GROUP CLASSIFICATION - AASHTO M-145</th></tr>
<tr><th colspan="2">A-1</th><th colspan="4">A-2</th><th rowspan="2">A-3</th><th rowspan="2">A-4</th><th rowspan="2">A-5</th><th rowspan="2">A-6</th><th colspan="2">A-7</th></tr>
<tr><th>A-1-a</th><th>A-1-b</th><th>A-2-4</th><th>A-2-5</th><th>A-2-6</th><th>A-2-7</th><th>A-7-5</th><th>A-7-6</th></tr>
<tr><td>PORTLAND CEMENT</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>5</td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td></tr>
<tr><td>FLY ASH</td><td></td><td></td><td></td><td></td><td>12</td><td>12</td><td>13</td><td>14</td><td>14</td><td>14</td><td></td><td></td></tr>
<tr><td>CEMENT KILN DUST (Pre-Calciner Plants)</td><td>5</td><td>5</td><td>5</td><td>5</td><td>5</td><td>5</td><td>6</td><td>✓</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>CEMENT KILN DUST (Other Type Plants)</td><td>10</td><td>10</td><td>10</td><td>11</td><td>11</td><td>11</td><td>12</td><td>12</td><td>12</td><td></td><td></td><td></td></tr>
<tr><td>HYDRATED LIME*</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>4</td><td>5**</td><td>5**</td></tr>
</table>
A blank in the table indicates the additive is not recommended for that soil group. Recommended amounts include a safety factor for loss due to wind, grading, and/or mixing. Pre-Calciner plants are identified on the Materials Division approved list for cement kiln dust.
✓ = Mix Design Required
* = Reduce quantity by 20% when quick lime is used, i.e. 4% x 0.8 = 3.2%, 5% x 0.8 = 4.0%, 6% x 0.8 = 4.8%
** = Use 6% when the liquid limit is greater than 50.
The process starts with initial soil testing to classify the soil and screen for soluble sulfates. If >500 ppm of sulfates are encountered, additional samples are tested throughout the length of the project. If >1,000 ppm of sulfates are encountered, a mellowing process during construction is likely needed. If >8,000 ppm of sulfates are present, calcium-based stabilization is not recommended.
</td></tr>
</table>

State	Mix Design Specifications
Tennessee	Lime and cement treated subgrade specifications are included in the *Standard Specification for Road and Bridge Construction* (Tennessee Department of Transportation, 2021). Section 302 provides guidelines for subgrade treatment with lime (hydrated lime or quicklime). Mix design is based on AASHTO T 99, Method C (American Association of State Highway and Transportation Officials, 2022) and considers moisture-density relationships using a 4-inch (101.60 mm) mold and soil material passing a ¾-inch (19.0 mm) sieve. No other guidance for mix design is included in the specification. Section 304 provides guidelines for subgrade treatment with cement. The percentage of cement to be used is based on tests of the in-place soil or select material.
Virginia	Sections 306 and 307 of the *Road and Bridge Specification* (Virginia Department of Transportation, 2020) provide guidelines for lime and hydraulic cement stabilization, respectively. However, no mix design guidance is included in this specification.

4.2.9 Availability of Construction Specifications for Subgrade Stabilization

Approximately 71 percent of responding states (20 states) have construction specifications for subgrade stabilization, and 29 percent (8 states) do not have any construction specifications (Figure 4.11).

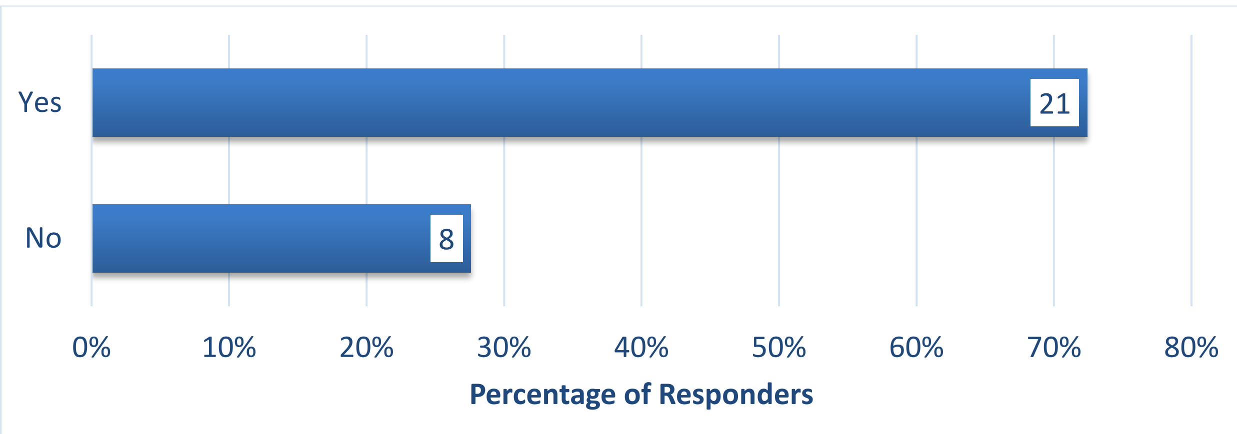

Figure 4.11. Availability of Construction Specifications for Subgrade Stabilization.

Among the states indicating available construction specifications, 15 states provided their specifications to the research team. These states included Alabama, Arkansas, California, Indiana, Kansas, Maryland, Minnesota, Nebraska, New Mexico, Ohio, Oklahoma, Oregon, Utah, Virginia, and Wisconsin. Table 4.7 summarizes these specifications.

Table 4.7. Summary of Construction Specifications.

State	Construction Specifications
Alabama	Sections 231 and 232 of the Alabama Department of Transportation's (2022) *Standard Specification of Highway Construction* provide guidelines for stabilized roadbed and lime stabilized roadbed, respectively. Section 231 describes how to prepare a roadbed for a base and pavement structure by stabilizing it with an approved local or commercial material. The work includes scarifying the roadbed;

<table>
<tr><th>State</th><th>Construction Specifications</th></tr>
<tr><td></td><td>incorporating the stabilizing material into the roadbed; and compacting the roadbed to the proper grade, section, and density.

Section 232 describes how to prepare a roadbed for an overlying base and paving structure by stabilizing it with a lime treatment. The work includes scarifying the roadbed, incorporating the lime, and processing the mixture to achieve the proper grade, section, and density in accordance with one of the following methods:
a. Class 1 lime stabilization consists of spreading and incorporating the specified percentage of lime in two increments: (1) spread first increment and conduct initial mixing and mellowing; and (2) spread second increment and conduct final mixing, compacting, and finishing in accordance with specifications. Mellowing softens the mixture to a loamy consistency.
b. Class 2 lime stabilization consists of spreading the specified percentage of lime and conducting initial mixing, mellowing, final mixing, compacting, and finishing in accordance with specifications.
c. Class 3 lime stabilization consists of spreading the specified percentage of lime and mixing, compacting, and finishing in accordance with specifications.</td></tr>
<tr><td>Arkansas</td><td>At locations where the engineer designates existing soils to be unstable and unable to be stabilized through normal drying and compacting efforts, an Arkansas DOT special provision (Arkansas Department of Transportation, (2018) allows the contractor, with the approval of the engineer, to utilize the following additives to expedite the drying process:
• Quicklime (dry) meeting the requirements of Subsection 301.03(b).
• Portland cement and/or fly ash meeting the requirements of Subsection 307.03(b).

The engineer determines which additive will be used. The rate of application is determined by trial and approved by the engineer. The spreading and mixing procedures must thoroughly and uniformly disperse the material into the soil. Any procedure that results in excessive loss of material or that does not achieve the desired results is immediately discontinued.</td></tr>
<tr><td>California</td><td>California specifications for stabilized soils are given in Section 24 of the Standard Specifications for Construction (California Department of Transportation, 2018). This section includes three subsections: 24-1 general, 24-2 lime stabilized soils, and 24-3 cement stabilized soils. Each section describes requirements for quality assurance, base material preparation, lime or cement application, quality control, mixing, compaction, quality control testing, materials, finish grading, curing, and payment.

Quality control testing requirements for lime stabilized soils are as follows:
<table>
<tr><th>Quality Characteristic</th><th>Test Method</th><th>Sampling Location</th><th>Minimum Frequency</th></tr>
<tr><td>Ground temperature at surface (before adding lime) and at full depth (during mixing operations)</td><td>--</td><td>Each temperature location</td><td>1 test per 20,000 ft^2, minimum 1 test per day</td></tr>
<tr><td>Lime application rate</td><td>Calibrated tray or equal</td><td>Roadway</td><td>1 test per 40,000 ft^2, minimum 2 tests per day</td></tr>
<tr><td>Gradation on mixed material</td><td>California Test 202</td><td>Roadway</td><td>1 test per 500 yd^3, minimum 1 test per day</td></tr>
<tr><td>Moisture content</td><td>California Test 226</td><td>Roadway</td><td>1 test per 500 yd^3 on each layer and each day during mixing and mellowing, minimum 1 test per day</td></tr>
<tr><td>Relative compaction</td><td>California Test 231</td><td>Roadway</td><td>1 test per 500 yd^3 on each layer, minimum 1 test per day</td></tr>
</table></td></tr>
</table>

<table>
<tr><th>State</th><th>Construction Specifications</th></tr>
<tr><td></td><td>
Quality control testing requirements for cement stabilized soils are as follows:
<table>
<tr><th>Quality Characteristic</th><th>Test Method</th><th>Sampling Location</th><th>Minimum Frequency</th></tr>
<tr><td>Air temperature before adding cement to basement material</td><td>--</td><td>Each temperature location</td><td>1 test per 20,000 ft^2, minimum 1 test per day</td></tr>
<tr><td>Moisture content of basement material before adding cement</td><td>California Test 226</td><td>Roadway</td><td>1 test per 1000 yd^2 per layer, minimum 1 test per day</td></tr>
<tr><td>Cement application rate</td><td>Calibrated tray or equal</td><td>Roadway</td><td>1 test per 20,000 ft^2, minimum 2 tests per day</td></tr>
<tr><td>Gradation on mixed material</td><td>California Test 202</td><td>Roadway</td><td>1 test per 1000 yd^2 per layer, minimum 1 test per day</td></tr>
<tr><td>Moisture content of mixed material</td><td>California Test 226</td><td>Roadway</td><td>1 test per 1000 yd^2 per layer, minimum 1 test per day</td></tr>
<tr><td>Moisture content of compacted material at the time of relative compaction testing</td><td>California Test 231</td><td>Roadway</td><td>1 test per 1000 yd^2 per layer, minimum 1 test per day</td></tr>
<tr><td>Relative compaction</td><td>California Test 231</td><td>Roadway</td><td>1 test per 1000 yd^2 per layer, minimum 1 test per day</td></tr>
</table>
</td></tr>
<tr><td>Indiana</td><td>
Section 215 of the Standard Specifications for Construction (Indiana Department of Transportation, 2021b) includes the following materials: Class C fly ash, lime, and Type 1 Portland cement. Soils for chemical stabilization must meet the following requirements:
<table>
<tr><th>Soil Property</th><th>Test Method</th><th>Requirement</th></tr>
<tr><td>Maximum dry density</td><td>AASHTO T 99</td><td>≥90 pcf</td></tr>
<tr><td>Organic material</td><td>AASHTO T 267</td><td>≤6%</td></tr>
<tr><td>Sulfate content</td><td>Indiana Test Method 510</td><td>≤1,000 ppm</td></tr>
</table>
Guidelines for compaction after mixing for chemical stabilization are as follows:
a. Compaction of Portland cement modified soils must begin 1 hour after mixing and be completed 3 hours after mixing.
b. Compaction of fly ash modified soils must occur within 4 hours after mixing.
c. Compaction of lime modified soils must occur within 24 hours after mixing.
Acceptance of chemically modified soils is determined by the following average and maximum deflection values from three LWD tests at random locations:
<table>
<tr><th>Material Type</th><th>Allowable Average Deflection (mm)</th><th>Maximum Deflection at a Single Test Location (mm)</th></tr>
<tr><td>Cement modified soils</td><td>0.27</td><td>0.31</td></tr>
<tr><td>Lime modified soils</td><td>0.30</td><td>0.35</td></tr>
</table>
If a DCP is used for compaction acceptance, blow counts of ≥15 and ≥14 are used for the top 6 inches and bottom 8 inches of a 14-inch lift, respectively. A blow count of ≥18 is used for an 8-inch lift. The LWD or DCP testing frequency is 3 tests per 1,400 cubic yards of chemically modified soil.
</td></tr>
<tr><td>Kansas</td><td>Section 302 and 303 of the Standard Specification for Construction (Kansas Department of Transportation, 2015) provide guidelines for lime treated and cement/fly ash treated subgrade, respectively.</td></tr>
</table>

<table>
<tr><th>State</th><th>Construction Specifications</th></tr>
<tr><td>Maryland</td><td>Section 502 of the Standard Specifications for Construction and Materials (Maryland Department of Transportation, 2022) provides guidelines for cement-modified bases and subgrades. This specification requires the following:

Construct a 500 foot long control strip to the specified lane width during the first day of production to verify that the construction process can meet the required gradation, spread rate for cement, and the roller pattern needed to obtain the specified density requirement for the entire project.
Compact to a density of at least 97 percent of the maximum dry density according to AASHTO T 134 (American Association of State Highway and Transportation Officials, 2019).
Final Acceptance and frequency of quality assurance testing will be based on the mix design, control strip, field compaction, depth check and consistency of pulverization, quality control plan, and application rate of Portland cement.
</td></tr>
<tr><td>Minnesota</td><td>Special Provision 2106 Subgrade Soil Modification (Minnesota Department of Transportation, (2020 provides guidelines for subgrade soil modification using Portland cement. Some important aspects regarding quality assurance in this specification are as follows:
<table>
<tr><th>Test Name</th><th>Rate</th><th>Method/Location</th></tr>
<tr><td>Depth check</td><td>1 test per 2,000 ft per machine width on each machine face</td><td>Grading and Base Manual, Section 5-692.284 and Form G&B-401</td></tr>
<tr><td>Cement yield</td><td>1 test per day</td><td>Grading and Base Manual, Section 5-692.286 and Form G&B-402</td></tr>
<tr><td>Calibration of cement application rate</td><td>1 test per design rate per vane feeder</td><td>Observe contractor</td></tr>
<tr><td>Cement</td><td>1 sample per project</td><td></td></tr>
<tr><td>Compaction (nuclear density)</td><td>Observe contractor</td><td>Grading and Base Manual, Section 5-692.282</td></tr>
<tr><td>Dynamic cone penetration p index test</td><td>3 tests per day after compaction to determine curing compliance</td><td>Grading and Base Manual, Section 5-692.255</td></tr>
</table></td></tr>
<tr><td>Nebraska</td><td>The Nebraska DOT’s Special Provision for Stabilized Subgrade (Nebraska Department of Transportation, (2021) includes two options for stabilization: cement and Class C fly ash.
The fly ash chemical requirements for a stabilized subgrade are as follows:
<table>
<tr><td>Silicon Dioxide (SiO_2) plus Aluminum Oxide (Al_2O_3) plus Iron Oxide (Fe_2O_3)</td><td>50.0% minimum</td></tr>
<tr><td>Sulfur Trioxide (SO_3)</td><td>5.0% maximum</td></tr>
<tr><td>Calcium Oxide (CaO)</td><td>20.0% minimum</td></tr>
<tr><td>Loss on ignition</td><td>12.0% maximum</td></tr>
</table>
Compaction and soil stiffness requirements are also defined. Soil stiffness, reflected in the deflection of the stabilized subgrade, is measured in-place by Nebraska DOT personnel using LWD tests on the processed material for acceptance. Additional definitions and requirements are as follows:

The deflection test is defined as the average of the fourth, fifth, and sixth drops of the deflectometer at one location. The first 3 drops are to be used to seat the LWD. The deflection value is defined as the average of 3 test locations. The deflection target value (DTV) is the lowest deflection value determined by using a control strip.
To determine the DTV, a new control strip is constructed when there is an observed change in material or as determined by the engineer. The control strip dimensions have a minimum length of 200 feet. The control strip construction is incidental to the pay item Stabilized Subgrade.
</td></tr>
</table>

State	Construction Specifications
	• During construction of the control strips, the contractor makes repeated compaction coverages. A single coverage is defined as the compacting of unbound material over a given point a single time. When the material is visibly densified, the engineer takes deflection tests at 3 locations to get an average deflection value. Following each test, additional coverages are conducted and deflection tests are taken until a DTV is established. • The DTV of the control strip is determined by compacting the processed material to a point that 3 consecutive coverages do not change the deflection by more than 10%. The DTV is based on the lowest average deflection test. The roller procedure must have a minimum of 6 consecutive coverages unless an alternate rolling pattern is approved by the engineer. A minimum of one pneumatic tire roller coverage is required. • The DTV will be re-evaluated when either deflection test measurements are consistently less than the DTV (i.e., when 3 out of 5 consecutive deflection tests are less than 0.8 of the DTV) or failing test results are consistently occurring, and adequate compaction is observed. • The optimum moisture content must be in an acceptable range of optimum moisture+2 percent. The moisture content will be determined according to AASHTO T 99 (American Association of State Highway Transportation Officials, 2022) at the Nebraska DOT's Materials and Research Central Lab. Acceptance testing requirements include the following: • A passing deflection test is defined as a deflection value less than 1.10 × DTV. • The moisture content of soil must be determined using Nebraska DOT's approved equipment and methods. Approved equipment includes a hot plate, stove, and microwave. Approved methods include the speedy moisture and laboratory oven methods. Moisture content results are reported to the nearest tenth of a percent. • The deflection and moisture content testing frequency is 1 test at one location every 1,500 square yards or less.
New Mexico	Section 203 A of the *Standard Specification of Highway and Bridge Construction* (New Mexico Department of Transportation, 2019) allows the contractor to choose any of the following stabilization options unless otherwise indicated in the contract: • Ripping, drying, and recompacting. • Excavation and replacement with material that meets or exceeds the project design R-value, with laboratory tests performed in accordance with AASHTO T 190 (American Association of State Highway and Transportation Officials, 2014). • Use of base course, reclaimed asphalt pavement, or select backfill. • Installation of underdrains and associated geotextiles and materials. • Geotextiles, geogrid base, and/or reinforcement materials. • Blending of existing materials with materials approved by the project manager. • Combinations thereof. If site conditions warrant a change in the stabilization method, no additional cost to the Department must result. The contractor must submit options to the project manager for concurrence prior to stabilization.
Ohio	Item 206 of the *Standard Specifications for Construction and Material* (Ohio Department of Transportation, 2019) details the use of cement and lime when constructing stabilized subgrades. When included in the plans, a mixture design for chemically stabilized soils must be performed according to Supplement 1120.
Oklahoma	Section 307 of the *Standard Specifications for Highway Construction* (Oklahoma Department of Transportation, 2019) provides guidelines for subgrade treatment using Portland cement, fly ash, cement kiln dust, hydrated lime, and quicklime.
Oregon	Section 00344 of Oregon DOT's *Standard Specifications for Construction* (Oregon Department of Transportation, 2021) (Oregon Department of Transportation, 2021) specifies treating subgrade using hydrated lime, granular quicklime, calcium chloride, sodium chloride, or Portland cement.

State	Construction Specifications
Utah	Utah DOT's *Cement Treated Subgrade* special provision (Utah Department of Transportation, XXXX) provides guidelines for constructing a cement treated subgrade.
Virginia	Sections 306 and 307 of the *Road and Bridge Specification* (Virginia Department of Transportation, 2020) provide guidelines for lime stabilization (lime, lime-fly ash) and hydrated cement stabilization, respectively.
Wisconsin	Wisconsin DOT's Fly Ash Subgrade Stabilization; SPV.0180 special provision (Wisconsin Department of Transportation, (2018) provides guidelines for fly ash stabilization.

4.2.10 Construction Acceptance Methods for Stabilized Subgrades

Approximately 73 percent of responding states (22 states) use density for construction acceptance, 47 percent (14 states) use moisture content, 67 percent (20 states) use depth of treatment, 30 percent (9 states) use deflection, and 37 percent (11 states) use other methods. Table 4.8 details other construction acceptance methods reported by respondents.

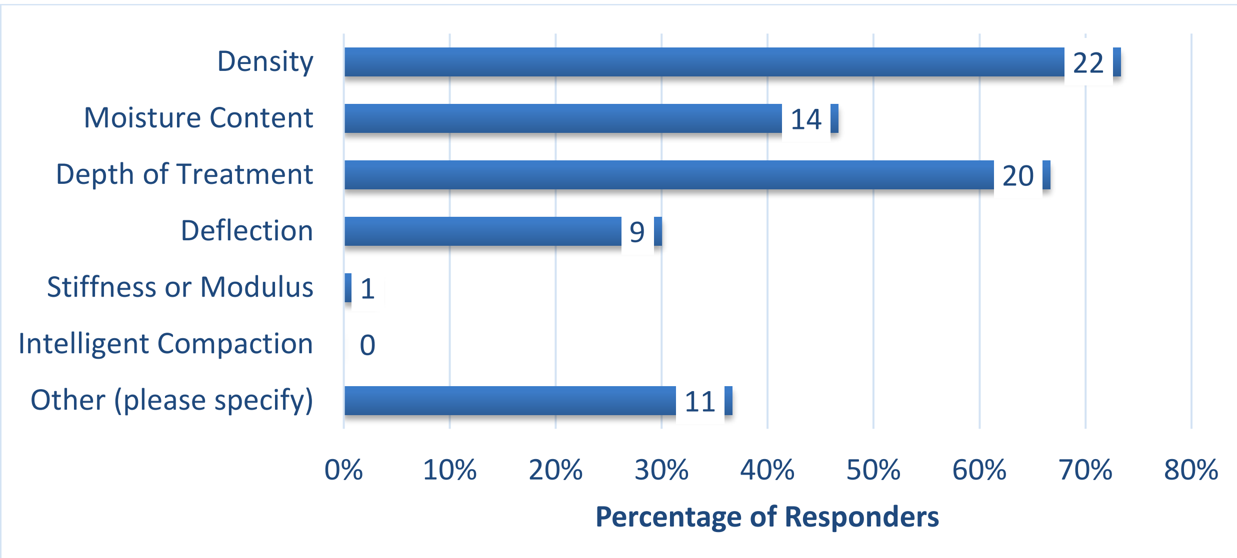

Figure 4.12. Construction Acceptance Methods.

Table 4.8. Other Construction Acceptance Methods.

State	Other Construction Acceptance Methods
California	Application rate of cement and lime
Delaware	Proof roll base placed on B borrow and No. 10 sieve screenings
Maryland	Control strip
Nebraska	Deflection with LWD or FWD
New Mexico	Ground displacement per specification
New York	*Successfully installed* determination by regional geotechnical engineer
Ohio	Proof rolling with a 35-ton static roller after 5 days of curing
Virginia	Follow Virginia test method (VTM-1), Sections 305-307 in the *Road and Bridge Specification* (Virginia Department of Transportation, 2020), and additional guidance regarding the geotextile stabilization process
Minnesota	Dynamic cone penetrometer

State	Other Construction Acceptance Methods
West Virginia	Roller pass
Wisconsin	No further appreciable consolidation by compaction/construction equipment

4.2.11 Use of Stabilized Subgrade Properties in the Pavement Design Process

Table 4.9 details the responding states' use of stabilized subgrade properties in the pavement design process.

Table 4.9. Use of Stabilized Subgrade Properties in Pavement Design.

State	Use of Stabilized Layer Properties in Pavement Design
Alabama	Yes, stabilized layers are assigned an AASHTO structural layer coefficient
Arizona	Coefficient of subgrade support
California	Yes, accounted for in asphalt concrete pavement design by using UCS of stabilized soils
Florida	Assign layer coefficient
Indiana	Based on resilient modulus testing, we recommend an M_R of 14,000 psi for pavement design
Kansas	A structural layer coefficient of 0.11/inch is used for all 3 treatments
Maryland	If the subgrade is stabilized, a maximum M_R of 10,500 psi may be used
Nebraska	An M_R of 30,000 psi is used for cement/fly ash and 20,000 psi is used for lime
Nevada	Yes, a 0.07 structural number is assigned as regular borrow material
New Mexico	Prefer to stabilize unstable subgrade mechanically using geogrid or geotextiles rather than chemically but have stabilized soils chemically using lime; in small areas, we remove the unstable subgrade and replace it with suitable material.
Minnesota	Yes, the resilient modulus
Ohio	Yes, when using global chemical stabilization, the subgrade M_R is increased by 36 percent for all pavements; for concrete, the elastic modulus of the aggregate base is increased from 30,000 to 36,000; for asphalt, the layer coefficient for the aggregate base is increased from 0.14 to 0.17
Oklahoma	Long-term durability of the stabilized subgrade is unknown and thus ignored in pavement design
Oregon	Subgrade M_R is increased according to the stabilization method
South Carolina	For a 300 psi mixture, use a_i=0.18; for a 450–600 psi mixture, use a_i=0.26
Texas	If proper mix design procedures are followed (Tex-120/121), structural credit up to 30–45 ksi can be assigned to stabilized subgrade; each district has their values in their pavement design standard operating procedures
Utah	Design as a chemically stabilized layer in pavement ME designs
Virginia	Yes, consider cement and lime stabilized materials as an input when using the AASHTOWare Pavement ME Design software and assign a layer coefficient for lime/cement stabilized base when using AASHTO's *Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials, 1993); no input is used for geotextiles with either method
Tennessee	Yes, considered as part of the structure
Wisconsin	Several methods can be used to provide additional subgrade strength including adding a granular material layer or stabilizing the subgrade (generally with fly ash); if one of these preapproved methods is incorporated into a project, the strength of the subgrade material is increased in the pavement design, resulting in a decreased structural pavement thickness

4.2.12 Methods to Address Potential Changes in Treated Subgrade Permeability

Table 4.10 details the methods to address potential changes in treated subgrade permeability reported by respondents.

Table 4.10. Methods to Address Potential Changes in Permeability.

State	Methods to Address Potential Changes in Permeability
Alabama	No
Arizona	No
California	No
Florida	No
Indiana	Do not know
Kansas	No
Maryland	Yes, generally recommend longitudinal underdrains on our roadways
Minnesota	No
Missouri	No
Nebraska	No
Nevada	No
New Mexico	No
New York	No
Ohio	No, most pavements have multiple lines of underdrains that extend through the stabilized subgrade and the aggregate base
Oklahoma	Not to my knowledge
Oregon	Where drainage is an issue, rock is often used as stabilization; when using cement stabilization, pavement edge drains may be used or adjacent ditches may be deepened
Rhode Island	No
South Carolina	No
Texas	Do not directly address permeability
Tennessee	No
Utah	No
Virginia	No
West Virginia	No
Wisconsin	No

4.2.13 Underdrain Installation Methods Relative to the Subgrade Stabilization Process

Table 4.11 details the states' individual responses regarding underdrain installation relative to the subgrade stabilization process.

Table 4.11. Underdrain Installation Methods.

State	Underdrain Installation Method
Alabama	After stabilization
Arkansas	Generally installed after installation, but only installed if subsurface conditions require
California	Generally, before stabilization
Delaware	After the undercut is performed
Florida	N/A
Indiana	Underdrains are installed after stabilization or modification; underdrains take care of surface water and also reduce moisture content below the stabilized material
Kansas	Unsure

State	Underdrain Installation Method
Maryland	Installed longitudinally along the outside pavement edge
Minnesota	N/A
Missouri	If underdrains are specified, they would likely be installed after stabilization, because stabilization would occur at a lower depth
Nebraska	After pavement placement and earth shoulder construction, they are trenched in; the foundation course extends 3 feet outside the pavement
Nevada	N/A
New Mexico	Very seldom install underdrains
New York	Depends on the project; if required, would be ideal to have the underdrain built first, however, underdrains are not always utilized in subgrade stabilization treatments
Ohio	Underdrains are trenched through the chemically stabilized layer using trenching machines after the 5-day curing period but prior to placing the aggregate base
Oklahoma	Specifications do not explicitly address this, however, it may be inferred from the separate underdrain and stabilization specifications that stabilization is performed after the underdrains have been installed and backfilled
Oregon	Do not typically install pipes as underdrains; typically use 1–3 feet of either 6 or 15 inches of rock as stabilization/drainage instead
Rhode Island	Use of stabilized subgrades has been primarily on rural roads with surface drainage
South Carolina	N/A
Texas	No clear guidance on how or when to use; please see Chapter 2, Section 8 of the *Pavement Manual* (Texas Department of Transportation, 2021)
Tennessee	Installed after the process
Virginia	See Section UD-4 Open Graded Drainage Layers in the *Road and Bridge Specification* (Virginia Department of Transportation, 2020)
Utah	N/A
West Virginia	N/A
Wisconsin	Not used

4.2.14 Lessons Learned and Other Details

Table 4.12 details lessons learned and other details related to subgrade stabilization.

Table 4.12. Lessons Learned and Other Details.

State	Lessons Learned and Other Details
Alabama	N/A
Arizona	N/A
Arkansas	N/A
California	Difficult to compact stabilized soils when moisture of underlying untreated soil is very high
Delaware	N/A
Florida	N/A
Indiana	Contractors prefer modification or stabilization; the subgrade is relatively uniform; modification/stabilization is not preferred in urban areas and areas with high groundwater
Kansas	N/A
Maryland	Still working out details on FWD acceptance testing regarding appropriate equations for determining M_R when testing directly on the subgrade
Minnesota	N/A
Missouri	N/A
Montana	N/A
Nebraska	N/A

State	Lessons Learned and Other Details
Nevada	N/A
New Mexico	Have had trouble with subgrade clays pumping up through geogrid into the base course on recent projects; are planning to try Mirafi® RS380i high-strength geotextile base reinforcement in an upcoming project
New York	Subgrade stabilizations are very project dependent; what works in some projects doesn't necessarily work in other projects; for the New York DOT, subgrade stabilizations are only designed for projects where new embankments are on soft soils; most subgrade stabilizations occur during construction when the contractor is having problems/issues
Ohio	It is important to test for sulfate content in the subgrade soil and set criteria for global chemical stabilization use due to the presence of sulfates; if sulfate contents are >5000 ppm to >8000 ppm, chemical stabilization is not used; weak subgrades are treated by undercutting; see Geotechnical Bulletin 1 for *Plan Subgrades* (Ohio Department of Transportation, 2021)
Oklahoma	Routinely test soils that may be used in stabilized subgrade for soluble sulfates and generally recommend that soils with >1000 ppm sulfates not be treated with routine calcium-based stabilizers; a few projects with high sulfates have used a mellowing process, but no standard procedure currently exists for this; a few projects have also used slag cement (research is ongoing); also researching use of X-ray fluorescence to measure stabilizer concentration (application rate)
Oregon	Western Oregon is very wet so commonly use 18 to 36 inches of rocks to both stabilize and improve drainage; see Section 00331 in the *Standard Specifications for Construction* (Oregon Department of Transportation, 2021)
Rhode Island	N/A
South Carolina	N/A
Tennessee	Installed underdrains that are not maintained cause additional challenges when clogged
Texas	Texas has very problematic (i.e., highly expansive, high sulfate, and organic) soils; given the variety of soils, each of the 25 districts adopts their own standard operating procedures; stabilization guidelines are provided by the Texas Department of Transportation (2019)
Utah	N/A
Virginia	Use of geotextile for subgrade stabilization is viewed as having some benefit; a structural (layer coefficient) value has been added but not yet quantified; project availability and process complexity pose challenges; weather can impact excavation requirements
West Virginia	N/A
Wisconsin	Have gone back and forth using one versus two bid items; currently use one bid item for *stabilization* and another bid item for *material*, which allows treatment rates to be adjusted when more/less material application is warranted and the contractor to be paid for the amount used

4.2.15 Additional Testing Burden when Developing a Mix Design and Constructing, Inspecting, and Accepting a Stabilized Subgrade Layer

Table 4.13 details responses related to the additional testing burden over the remove and replace method when developing a mix design and constructing, inspecting, and accepting a stabilized subgrade layer.

Table 4.13. Additional Testing Burden.

State	Additional Testing Burden
Alabama	Cutting cores from soil cement for acceptance testing is problematic

State	Additional Testing Burden
Arizona	No
Arkansas	N/A
California	Yes, contractor has to change application rate of cement or lime depending on changing soil environment that is exposed during construction
Delaware	No
Florida	No, samples were collected to perform a mix design prior to construction using Eades and Grim pH lime testing
Indiana	Use a LWD test that takes two minutes to perform
Kansas	N/A
Maryland	Still working out details on FWD acceptance testing regarding appropriate equations for determining M_R when testing directly on the subgrade
Minnesota	No
Missouri	N/A
Montana	If chemical stabilization is used, this is a concern; also no contractors in Montana currently specialize in this type of work
Nebraska	N/A
Nevada	N/A
Nevada	N/A
New Mexico	N/A
New York	No testing; acceptance is based upon the contractor successfully completing the subgrade stabilization recommendations made by the regional geotechnical engineer
Ohio	No, everything is similar whether chemically stabilization is used or not; mainly rely on consultants for mix design sampling and testing, construction compaction testing, and strength gain verification testing
Oklahoma	Time-consuming nature of mix design led to development of a table containing recommended application rates based on AASHTO classification and stabilizer types
Oregon	Use test strips to find the best cement percentage and compaction procedures for cement treatment
Rhode Island	None
South Carolina	N/A
Texas	Proper mix design requires time and effort; need to close the loop with the inspection; forensics conducted on premature failures have revealed variability in stabilization depth; mix design sets targets, but these targets are not enforced during construction
Tennessee	Depends on staffing availability and experience
Utah	N/A
Virginia	Cost is the primary determinant for stabilization; limitations also exist regarding technology availability; plan to use more geotextile fabrics in the future
West Virginia	N/A
Wisconsin	Added workload to an already stretched-thin staff

4.2.16 Supplemental Files

At the end of the survey, respondents were asked to provide any supplemental files that may benefit this research. Two files containing guidelines for subgrade stabilization (GB1_Plan Subgrades) and soil modification mix design were provided by Ohio and Oklahoma DOT personnel, respectively. These guidelines were reviewed for developing the specifications for subgrade stabilization.

4.2.17 Contact Details for the Contractors and Consultants Involved in Subgrade Stabilization

Similarly, respondents were asked to provide contact information for the various contractors and consultants involved in subgrade stabilization in their state. Information was provided by DOT personnel in Arkansas, California, Delaware, Indiana, Montana, Ohio, Oklahoma, Rhode Island, and New York.

4.3 Conclusions from State DOT Surveys

The survey of state DOT personnel provided information on project selection methods, testing requirements, mix design methods, construction specifications, and pavement design procedures to incorporate subgrade stabilization. This information was used to develop guidance documents and specifications for the MDOT.

CHAPTER 5 DEVELOP GUIDANCE DOCUMENTS

The research team developed guidance documents for project selection, mix design, and construction of chemically stabilized subgrades. The document development process considered the results of the literature review, survey of state DOTs, and information obtained from MDOT staff. Several rounds of extensive reviews of these documents were completed by the research team and the MDOT Research Advisory Panel members. The MDOT project manager solicited feedback from MDOT construction staff throughout the review process. The documents developed include the following:

- Technical Guide for Selection of Pavement Projects for Chemical Stabilization of Subgrade Soils.
- Guidelines for Mix Design of Chemically Stabilized Soils in Pavement Structures.
- Guidelines for Construction of Chemically Stabilized Soils in Pavement Structures.

Each of these guidance documents are detailed below.

5.1 Project Selection Guidance Document

The project selection guidance document was developed as a standalone document for MDOT staff to aid them in selecting projects for subgrade stabilization. Based on the actual subgrade conditions encountered during scoping and soil investigation, the pavement designers can use these guidelines to determine whether subgrade stabilization should be recommended for the long-term performance of the pavement structure or short-term modification of subgrade soil to facilitate construction. The following sections are included in this guidance document:

1. Introduction.
2. Field investigation guidelines.
3. Criteria for subgrade stabilization.
4. Decision tree for selection of subgrade stabilization additives based on soil characteristics.

The project selection guidance document is included in Appendix B of this report.

5.2 Mix Design Guidance Document

The mix design guidance document provides guidelines for MDOT engineers when reviewing contractor-developed mix designs. The following sections are included in this document:

1. Introduction (including a brief description of the chemical stabilization mechanism).
2. Soil sampling.
3. Basic material tests.
4. Additive selection and mix design (for lime, cement, lime-fly ash, and lime-cement).

5. Mix design reports.
6. Materials.

The mix design guidance document is included in Appendix C of this report.

5.3 Construction Guidance Document

The construction guidance document provides detailed information on the construction process for stabilized subgrades. This document will aid MDOT construction staff when reviewing construction documents submitted by the contractor. This document also provides information regarding quality assurance in subgrade stabilization projects.

The following main sections are included in this guidance document:

1. General description.
2. Materials.
3. Equipment.
4. Preconstruction.
5. Construction of stabilized subgrades.
6. Inspection and testing.
7. Measurement, documentation, and payment.

The construction guidance document is included in Appendix D of this report.

CHAPTER 6 DEVELOP A CONSTRUCTION SPECIFICATION

6.1 Introduction

A construction specification for subgrade stabilization was developed based on previous MDOT construction specifications, other State's specifications reviewed during this research project, findings from the literature review, and extensive input and collaboration during working meetings with the MDOT Research Advisory Panel members. The research team also gathered input from MDOT staff with relevant project experience and performed construction observations during the I-275 (MDOT JN 111073) and the US-24 (MDOT JN 132102) reconstruction projects in Wayne County, Michigan.

6.2 Construction Specification for Subgrade Stabilization

The developed specification includes the following sections:

- Description: This section describes the work included in the specification, the minimum qualifications of the contractor, and other general details.
- Materials: This section details the materials used in subgrade stabilization.
- Contractor provided mixture design: This section details the mixture design procedure for subgrade stabilization using lime, lime-fly ash, cement, or lime-cement.
- Equipment: This section describes the equipment requirements for subgrade stabilization.
- Construction: This section details the construction procedures, including test strip construction, subgrade preparation, chemical application, initial and final mixing, compaction, finishing, and curing and protection.
- Field quality control: This section details the contractor's field quality control requirements.
- Field quality assurance: This section details the MDOT field quality assurance requirements.

The developed construction specification is provided in Appendix E of this report.

6.3 Construction Observation of I-275 Cement Stabilized Subgrade Project (MDOT JN 111073)

As part of the I-275 (MDOT JN 111073) reconstruction project in Wayne County, Michigan, the research team observed the test strip construction, quality control tests, and quality assurance tests during the first day of work. Figures 6.1–6.9 show photos of the construction operations observed during this visit.

Figure 6.1. Spreading of Cement on I-275.

Figure 6.2. Pulverizing on I-275.

Figure 6.3. Rolling with Sheep Foot Roller on I-275.

Figure 6.4. Rolling with Smooth Drum Rollers on I-275.

Figure 6.5. Grading with the Motor Grader on I-275.


Figure 6.6. Underdrain Construction on I-275.

Figure 6.7. Nuclear Density Test on I-275.

Figure 6.8. Light Weight Deflectometer Test on I-275.

Figure 6.9. Depth Check Using Phenolphthalein Solution on I-275.

6.3.1 Strength Development of the Stabilized Subgrade on I-275

The MDOT team collected DCP and LWD data during the subgrade stabilization process. This data collection aimed to establish a strength development timeline before and after the construction process. The data collection process began before the stabilizing agent was applied and continued at different time intervals after the compaction process was completed.

During the DCP data collection, the number of blows required for 12 inches of penetration was recorded after 1 seating drop. Similarly, LWD deflection was recorded on the stabilized surface after 3 seating drops. Table 6.1 shows the stations and timelines of the testing program.

Table 6.1. Collection of DCP and LWD Data on I-275.

Stations	Testing Timeline at Each Station						
932+35	Before stabilization	Immediately after stabilization	1-day cure	2-day cure	3-day cure	4-day cure	5-day cure
936+46							
940+26							
944+96							
950+00							

Figures 6.10 and 6.11 show the DCP and LWD data plots, respectively, for all five locations at the time of testing. The DCP index reached the threshold value of 14 mm/blow less than 24 hours after cement stabilization. This threshold value was established based on other state's specifications and the anticipated CBR value of the stabilized subgrade and is included in the developed construction specification for subgrade stabilization. All DCP values fell below the threshold value after 24 hours of curing, showing satisfactory strength development after stabilization. Deflections under the LWD stabilized after approximately 24 hours. Figure 6.12 shows the percentage frequency diagram for the LWD deflection data.

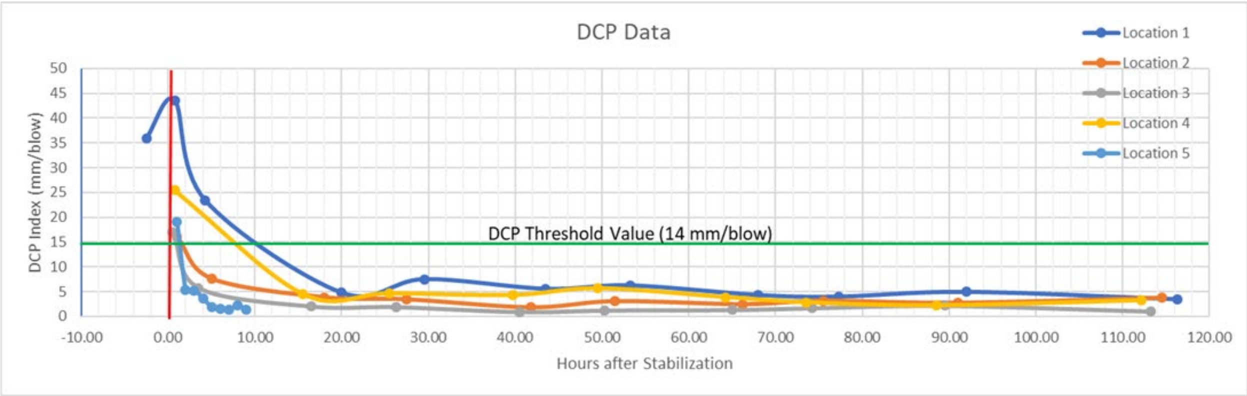

Figure 6.10. Variation of DCP Data over Time on I-275.

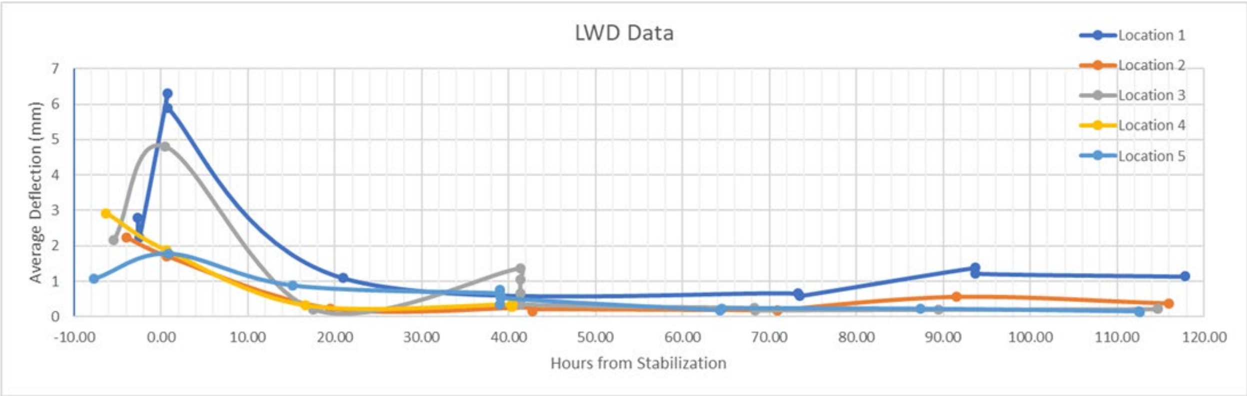

Figure 6.11. Variation of LWD Data over Time on I-275.

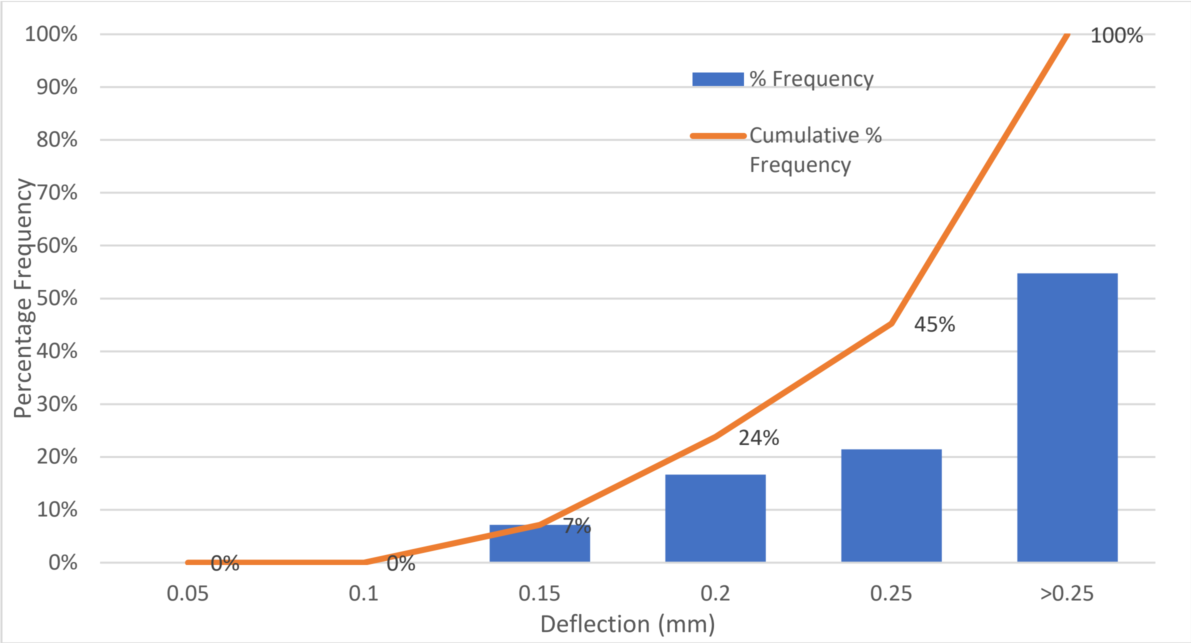

Figure 6.12. Percentage Frequency Diagram for LWD Deflection Data on I-275.

The Indiana DOT has established a maximum average LWD deflection value of 0.14 mm for construction acceptance of cement stabilized subgrade after 7 days of curing. Since the LWD data collection was ended after 5 days of construction, an evaluation was conducted to determine the LWD deflections after 24 hours of curing. As shown in Figure 6.12, less than 7 percent of the test locations had deflection values less than 0.14 mm after approximately 24 hours of curing. This finding suggests that more research is required for the MDOT to establish an acceptance threshold value for LWD for subgrade stabilization.

6.4 Construction Observation of US-24 Cement Stabilized Subgrade Project (MDOT JN 132102)

As part of the US-24 (MDOT JN 132102) reconstruction project in Wayne County, Michigan, the research team observed the stabilized subgrade construction, quality control tests, and quality assurance tests during the first day of work. The MDOT team again collected DCP and LWD data for the stabilized subgrade. Figures 6.13–6.15 show photos of the construction operations observed during this visit.

As shown in Figure 6.13, dusting was observed during cement spreading when the prevailing wind conditions were high. This phenomenon could pose a danger to the traveling public and property owners in the surrounding area. If the MDOT determines that the prevailing wind conditions are unsuitable for applying the stabilizer in powder form, wet methods (i.e., using the stabilizer in slurry form) should be recommended. These recommendations are included in the *Guidelines for Construction of Chemically Stabilized Soils in Pavement Structures* in Appendix D of this report.

Figure 6.13. Spreading of Cement During Chemical Application on US-24.

Figure 6.14. Mixing of Cement and Soil Using an Excavator in Tight Areas (Where a Rotary Pulverizer Cannot Reach) on US-24.

Figure 6.15. Dynamic Cone Penetration Testing on US-24.

As shown in Figure 6.14, mixing the stabilizer and soil with the rotary pulverizer was not possible in tight construction areas often found in urban road construction projects. In these small areas, the contractor may need to use alternative mixing techniques (i.e., using excavators or similar equipment). The construction inspectors need to pay extra attention to these alternative mixing operations to ensure that proper mixing consistencies and depths are achieved.

6.4.1 Strength Development of Stabilized Subgrade on US-24

The MDOT team again collected DCP and LWD data during the subgrade stabilization process. The DCP and LWD testing was conducted immediately after stabilization and up to 24 hours after stabilization. At most locations, the threshold DCP index of 14 mm/blow was achieved within 24 hours of subgrade stabilization (Figure 6.16).

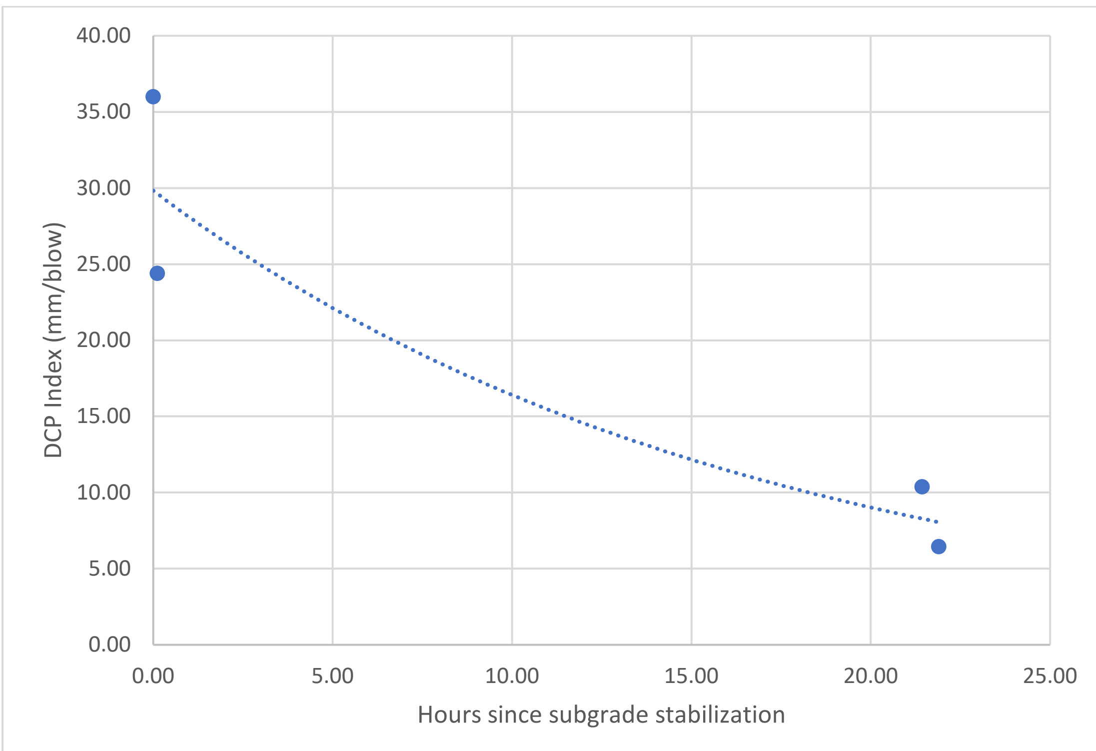

Figure 6.16. Variation of DCP Index over Time at Sta. 48+50 on US-24.

Figure 6.17 shows the percentage frequency diagram for the LWD deflection data. Most of these data were collected immediately after stabilization or within 24 hours of stabilization. A threshold value for LWD based construction acceptance still needs to be established if MDOT is planning to use LWD as a quality assurance tool.

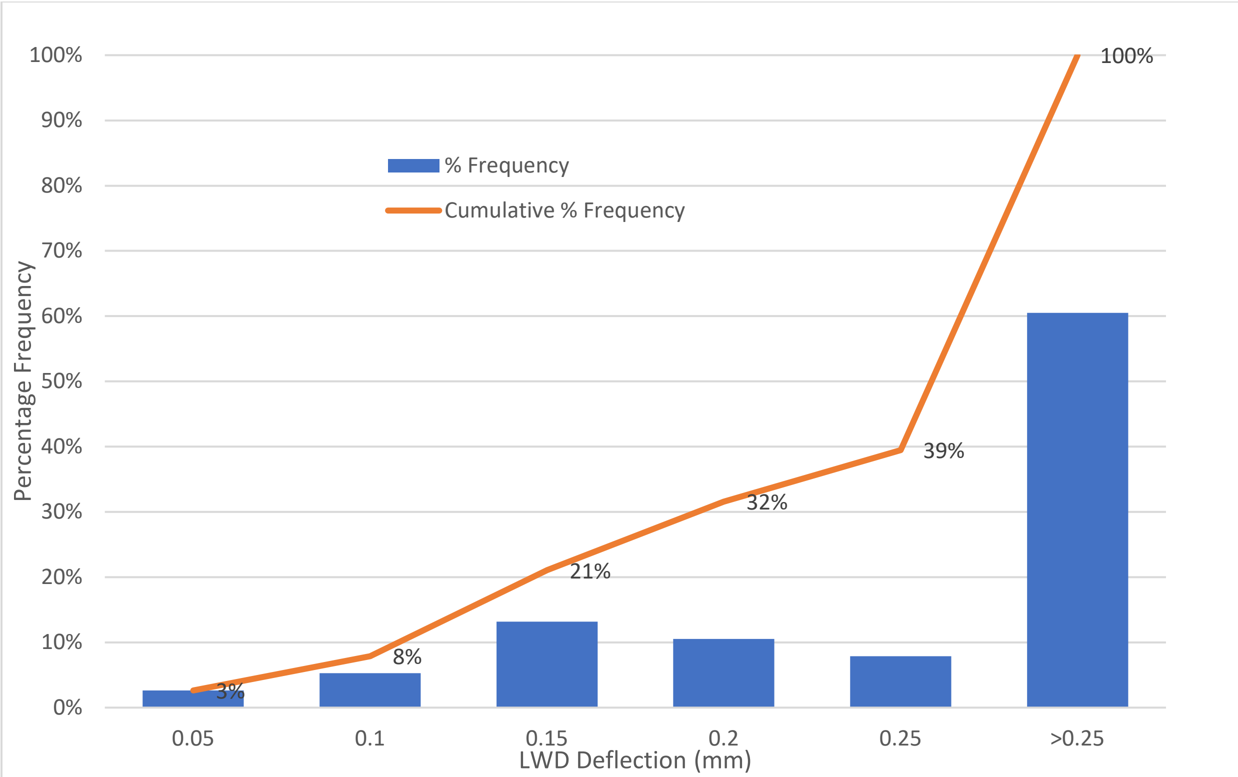

Figure 6.17. Percentage Frequency Diagram for LWD Data Collected within 24 hours after Stabilization on US-24.

CHAPTER 7 PAVEMENT DESIGN INPUTS FOR STABILIZED SUBGRADE

7.1 Introduction

Lime and cement stabilization improve the properties of subgrade soils and hence are anticipated to improve the performance of pavement structures. These improvements are documented in laboratory and field studies summarized in Chapters 2 through 5 of this report. Most U.S. states have recommendations for structural layer coefficients used in the 1993 AASHTO pavement design for the stabilized layers. These layer coefficients range from 0.07 to 0.11 for lime-stabilized subgrade layers and 0.07 to 0.20 for cement-stabilized subgrade layers. MDOT uses a multiplier of 1.36 to the in-situ subgrade resilient modulus when subgrade stabilization is incorporated in AASHTO 1993 design. For mechanistic-empirical (ME) pavement design, a few states provide guidelines for resilient modulus (M_r) values ranging from 15,000 psi to 30,000 psi or a multiplier to the in-situ subgrade resilient modulus. The Ohio Department of Transportation uses a multiplier of 3.9 for lime-stabilized subgrade and 4.7 for cement-stabilized subgrade. The Minnesota Department of Transportation uses a multiplier of not more than 2 for any stabilized subgrades. The Michigan Department of Transportation currently uses a multiplier of 4 for any stabilized subgrades (based on previous MDOT research, Ohio DOT research, and NCHRP 789 findings).

The other properties to consider for ME pavement design include changes in soil mixture characteristics such as percentage passing #200 sieve (P200), Liquid Limit (LL), Plasticity Index (PI), Saturated hydraulic conductivity (k), and other subgrade soil parameters included in the ME pavement design. These changes are discussed in Chapter 2 of this report.

The goals of analyzing pavement design inputs for stabilized subgrade are as follows.

1. Review pavement design inputs used by other State DOTs and compare them with the current MDOT practice.
2. Conduct sensitivity analysis of the MDOT-specified resilient modulus multiplier for stabilized subgrade compared to other State DOT multipliers for AASHTOWare Pavement ME analysis.
3. Consider changes to other geotechnical parameters such as LL, PI, and gradation for subgrade stabilization in AASHTOWare Pavement ME analysis and document the effect of those parameters in terms of pavement performance.
4. Summarize the analysis findings for future pavement design enhancements and provide recommendations.

The scope of the analysis in this study is limited to a deterministic set of variables established jointly by the research and MDOT RAP team. It is outside the scope of this project to perform extensive optimizations of the pavement design or to comment on the calibration models and non-subgrade related variables used by MDOT.

Further, the effect of subgrade stabilization in the AASHTO 1993 method was not conducted based on discussions with the MDOT RAP team. As previously noted, the current practice of MDOT is to use a multiplier of 1.36 to the in-situ subgrade resilient modulus when the stabilized subgrade is incorporated into the design. MDOT does not use structural coefficients for the stabilized layer as some of the other State DOTs do. Predominantly, MDOT uses the AASHTO 1993 method only to establish initial designs for AASHTOWare Pavement ME analysis as it moves towards exclusively using Pavement ME for pavement designs.

Only MDOT-provided final pavement designs were analyzed to establish the sensitivity of pavement design inputs using AASHTO Pavement ME software. In terms of the following analyses, these final designs will be referred to as the initial pavement design. For the analysis of ME pavement designs, AASHTOWare Pavement ME software version 2.6.2.2 was used with the latest MDOT calibration factors (2023) for Hot Mix Asphalt (HMA) and Jointed Plain Concrete Pavement (JPCP) pavement designs. See Appendix F for the calibration coefficients used for Pavement ME designs. The current MDOT criteria for final designs using Pavement ME include the following:

- The minimum thicknesses are 6.5" for flexible sections, 9" for JPCP freeway sections, and 8" for JPCP non-freeway sections.
- The ME design pavement thickness is limited to ±1 inch from the final AASHTO 1993 thickness.
- JPCP widened slab sections are designed using the standard width of 12 feet, and design thicknesses are reduced by up to 1 inch, subsequent to the maximum allowable difference and no less than the minimum thickness. Note that this practice is followed because the widened slab input of Pavement ME is extremely sensitive, which has resulted in non-practical designs that are overly thin.

7.2 Pavement Designs Considered for the AASHTOWare Pavement ME Analysis

The following pavement designs from different MDOT regions, climate areas, and traffic conditions were considered, as shown in Table 7.1. Both HMA and JPCP pavement designs were analyzed for each project.

Table 7.1. Pavement Designs Considered for the Analysis.

MDOT Region/County	MDOT Contract ID	Project Location	Initial AADTT*	Subgrade Soil Type	Climate Station
Southwest/ Berrien County	11015-132824	I-94 from Red Arrow Highway – Britain Ave.	12,240	Sandy clay	Benton Harbor
North/Emmet County	24012-131801	US-31 from Indiana St. to Milton Rd.	403	Poorly graded sand/silty sand	Pellston
Superior/Iron County	36051-203897	US-2 from Michigan/Wisconsin State Line – County Rd 424	255	Poorly graded sand/silty sand	Iron Mountain
Bay/Lapeer County	44044-204418	I-69 from M-24 – Wilder Rd.	4,527	Sandy clay	Flint
Metro/Oakland County	63022-124103	I-96 from Kent Lake Rd. – I-275 Interchange	8,480	Clay	Pontiac
Metro/Wayne County	82053-132102	US-24 from Grand River Ave. – 8 Mile Rd.	1,740	Sandy silt	Detroit

* - Initial AADTT = Initial Year Two-way Annual Average Daily Truck Traffic

7.3 Pavement Design Parameters Used for the Analysis

The Subgrade design inputs in Table 7.2 were considered for sensitivity analysis of the incorporation of subgrade stabilization for HMA and JPCP pavement designs. Most inputs were obtained from the *MDOT User Guide for ME Pavement Design (2021)*. Table 7.2 below shows MDOT recommended subgrade resilient modulus values (as per an annual representative value), Liquid Limit (LL) Values, Plasticity Index (PI) Values, and Dry Unit Weight (MDD) Values for different subgrade soil types.

Table 7.2. Subgrade Design Inputs (MDOT User Guide for ME Pavement Design, 2021).

Subgrade soil type (Unified Soil Classification)	Resilient Modulus range (psi)	LL	PI	MDD (lbs/ft^3)
Lean Clay (CL)	3,700-5,100	32.5	15.2	113.5
Silt (ML)	3,700-5,100	21.0	21.0	106.2
Clayey Sand (SC)	3,700-5,100	32.8	17.2	110.6
Clayey Sand-Silty Sand (SC-SM)	4,200-5,800	17.7	5.6	118.8

Silty Sand (SM)	4,400-6,000	17.0	3.0	112.1
Poorly Graded Sand (SP)	5,500-7,500	0	0	110.6
Poorly Graded Sand- Silty Sand (SP-SM)	5,900-8,100	15.5	5.0	113.8

Table 7.3 shows the typical subgrade soil gradations as provided in *MDOT User Guide for ME Pavement Design.*

Table 7.3. Subgrade Soil Gradations (MDOT User Guide for ME Pavement Design, 2021).

Sieve	CL	ML	SC	SC-SM	SM	SP	SP-SM
3/8”	99.9	100	99.7	99.9	99.9	98.2	96.3
No. 4	99.5	99.4	98.5	98.6	98.6	96.2	92.5
No. 10	97.7	98.0	94.2	94.0	94.2	93.7	87.2
No. 20	96.0	93.4	91.2	84.2	88.8	89.7	79.4
No. 40	90.7	83.2	82.2	69.2	73.3	75.2	66.1
No. 100	68.3	64.5	53.5	38.8	37.4	9.0	17.5
N0. 200	57.5	55.1	40.9	29.9	26.7	2.5	6.6

7.4 Pavement Design Analysis Options

The following analysis options were considered for sensitivity analysis of stabilized subgrade pavement design inputs. The starting pavement designs were based on the final pavement designs provided by MDOT for both HMA and JPCP.

<u>Option 1:</u> Use four in situ subgrade types (CL, SC, SM, and SP-SM). Use the MDOT's average M_r values (Table 7.4)

<u>Option 2a:</u> Use four in situ subgrade types (CL, SC, SM, and SP-SM) with their average M_r values. Add a 12" stabilized subgrade layer (keep the existing subgrade types), but for M_r, multiply the existing M_r by (i) 4 (Michigan method), (ii) 2 (Minnesota method), and (iii) 4.7 (Ohio method).

Option 2b: Same as 2a (i to iii). Change the 12" stabilized subgrade layer to SP-SM.

Option 2c: Four in situ subgrade types (CL, SC, SM, and SP-SM). Use the same types for the 12" stabilized layer, but use M_r value of 17,380 psi (with EICM).

Option 2d: Four in situ subgrade types (CL, SC, SM, and SP-SM). Use only SP-SM for the 12" stabilized layer, and use M_r value of 17,380 psi (with EICM).

The details of these analysis options are given beloq.

1. **Analysis Option 1**: Change the existing subgrade types to CL, SC, SM, and SP-SM to assess the impacts of different soil types. Perform AASHTOWare Pavement ME designs using soil parameters for each soil type as given in Tables 7.2 and 7.3 for non-stabilized pavement sections. In the AASHTOWare Pavement ME software, the subgrade moduli values were inserted as an annual representative value, without considering the Enhanced Integrated Climate Model (EICM) (which is MDOT's standard practice). The in-situ subgrade resilient modulus values used in the AASHTOWare Pavement ME software analysis are shown in Table 7.4.

Table 7.4 In situ Subgrade Resilient Modulus Values (As annual representative values).

Subgrade Soil Type	Average Resilient Modulus (psi)
CL	4,400
SC	4,400
SM	5,200
SP-SM	7,000

2. **Analysis Option 2:** Add a 12-inch-thick stabilized subgrade layer with the following four variations:
    a. **Analysis Option 2a**: Change only the M_r value of the stabilized layer with the in-situ subgrade types with the same geotechnical parameters using the following subgrade resilient multipliers for the stabilized layer as an annual representative value (without using EICM)
        i. Michigan method – a multiplier of 4
        ii. Minnesota method – a multiplier of 2
        iii. Ohio cement stabilized method – a multiplier of 4.7 (Ohio lime stabilized multiplier of 3.9 was not used as it was very close to the Michigan multiplier of 4.0)

Resilient modulus values for in situ and stabilized layers used in the AASHTOWare Pavement ME software analysis are shown in Table 7.5. All other geotechnical parameters are from Tables 7.2 and 7.3 for the corresponding soil types.

Table 7.5 In-situ and Stabilized Subgrade Resilient Modulus Values for Analysis Option 2a.

In situ and Stabilized Subgrade Soil Type	In situ Subgrade Resilient Modulus (psi)	Stabilized Subgrade Resilient Modulus Values (psi)		
		Michigan Method	Minnesota Method	Ohio Cement Method
CL	4,400	17,600	8,800	20,680
SC	4,400	17,600	8,800	20,680
SM	5,200	20,800	10,400	24,440
SP-SM	7,000	28,000	14,000	32,900

b. **<u>Analysis Option 2b</u>**: Change the stabilized layer type to SP-SM (without using EICM and the same multipliers as with step (a)) with all the geotechnical parameters for SP-SM soil type to account for the change in geotechnical parameters due to stabilization as reported in previous literature (Change in P200, LL, PI, and hydraulic conductivity).

Resilient modulus and soil types for in situ and stabilized layers used in the AASHTOWare Pavement ME software analysis are shown in Table 7.5. All other geotechnical parameters will be those of SP-SM from Tables 7.2 and 7.3.

c. **<u>Analysis Option 2c</u>**: Change the stabilized layer with the in situ subgrade soil type to use a M_r value of 17,380 psi with EICM. Since a minimum CBR value of 20 is required for the stabilized layer, based on the general relationship of $M_r = 2555 \times CBR^{0.64}$, a minimum M_r of 17,380 psi was used for all stabilized soil types used in the analysis.

Resilient modulus and soil types for in situ and stabilized layers used in the AASHTOWare Pavement ME software analysis are shown in Table 7.6.

Table 7.6 In situ and Stabilized Subgrade Soil Types and Resilient Modulus Values for Analysis Option 2c.

In situ and Stabilized Subgrade Soil Type	In situ Subgrade Resilient Modulus (psi) as an annual representative value	Stabilized Layer Resilient Modulus (with EICM analysis)
CL	4,400	17,380
SC	4,400	17,380
SM	5,200	17,380
SP-SM	7,000	17,380

d. **<u>Analysis Option 2d</u>**: Change the stabilized layer type to SP-SM soil type with a M_r value of 17,380 psi and modifying the stabilized layer resilient modulus with EICM.

Resilient modulus and soil types for in situ and stabilized layers used in the AASHTOWare Pavement ME software analysis are shown in Table 7.7. All other geotechnical parameters will be those of SP-SM from Tables 7.2 and 7.3.

Table 7.7 In situ and Stabilized Subgrade Soil Types and Resilient Modulus Values for Analysis Option 2d.

In situ Subgrade Soil Type	In situ Subgrade Resilient Modulus (psi)	Stabilized Layer Soil Type	Stabilized Layer Resilient Modulus (with EICM analysis)
CL	4,400	SP-SM	17,380
SC	4,400	SP-SM	17,380
SM	5,200	SP-SM	17,380
SP-SM	7,000	SP-SM	17,380

All together, for each project and each pavement type (HMA and JPCP), 4 non-stabilized ME pavement designs with Option 1, 12 ME pavement designs with Option 2a, 12 ME pavement designs with Option 2b, 4 ME pavement designs with Option 2c, and 2 ME pavement designs with Option 2d was performed. This analysis resulted in a total of 34 ME pavement designs for HMA and 34 ME designs for JPCP for each project.

7.5 AASHTOWare Pavement ME Analysis results for HMA Designs

The following section provides the input data, initial pavement design used for analysis, and the results of all the analysis options for MDOT project JN 132824, I-94 from Red Arrow Highway to Britain Avenue in Berrien County in the Southwest Region. A similar analysis approach was followed for the other remaining projects, and summary results are included in Section 7.5.2 of this report.

7.5.1 I-94 Reconstruction in Berrien County MDOT JN 132824 HMA Pavement Design

The AASHTOWare Pavement ME design inputs provided by MDOT for this project are shown in Figure 7.1. As shown in Figure 7.1, the pavement structure consists of 14.5 inches of HMA, followed by 6 inches of dense graded aggregate base, followed by 18 inches of sand subbase over a sandy clay subgrade material. The pavement was designed for 36.6 million cumulative number of heavy trucks over 20 years.

Layer type	Material Type	Thickness (in)
Flexible	4EMH_64-28	2.3
Flexible	3EMH_64-28	3.8
Flexible	2EMH_58-22	8.0
NonStabilized	Dense-Graded Aggregate Base	6.0
NonStabilized	Sand Subbase	18.0
Subgrade	Sandy Clay Subgrade	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	11.5
Air voids (%)	6.1

Age (year)	Heavy Trucks (cumulative)
2023 (initial)	12,240
2033 (10 years)	17,833,200
2043 (20 years)	36,578,300

Figure 7.1. HMA Pavement Design for I-94 Reconstruction in Berrien County (MDOT JN 132824).

Figure 7.2 shows the AASHTOWare Pavement ME predicted performance for the above initial design used for analysis.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	118.69	95.00	100.00	Pass
Permanent deformation - total pavement (in)	0.50	0.24	95.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	20.00	16.40	95.00	98.78	Pass
AC thermal cracking (ft/mile)	1000.00	693.80	95.00	99.18	Pass
AC top-down fatigue cracking (% lane area)	25.00	16.36	95.00	99.90	Pass
Permanent deformation - AC only (in)	0.50	0.21	95.00	100.00	Pass

Figure 7.2. Performance Prediction Indicators for JN 132824 (Initial Design– non-stabilized analysis).

As seen in Figure 7.2, the design has a passing performance for all the distress types.

The next step is to follow the analysis steps provided in Section 7.4 to evaluate the effect of adding a stabilized subgrade layer in the design.

The predicted design life of the pavement sections was calculated by running the pavement design for an analysis period of 50 years. Predicted design life for non-stabilized pavement sections and stabilized pavement sections was obtained when one of the predicted distress types (IRI, Permanent deformation, AC bottom-up cracking %, AC top-down cracking %, AC thermal cracking, Permanent deformation – AC only) exceeded the target distress value (shown in Figure 7.2) from the *MDOT User Guide for ME Pavement Design (2021, March)*. However, AC thermal cracking was ignored and other distress types were considered to determine predicted design life. Based on the results obtained, only the AC bottom-up cracking (BU Cracking) performance shows an improvement due to subgrade stabilization. This is an expected performance improvement since providing a stable layer above the subgrade will reduce the HMA layer deformation, and hence, improve the AC bottom-up cracking performance. Tables 7.8 to 7.10

show the analysis results for I-94 Reconstruction in Berrien County for Option 1, Options 2a and 2b, and Options 2c and 2d, respectively. Only the AC Bottom-up cracking % (BU Cracking %) at 20-year design life and predicted pavement design life are shown in the table.

Table 7.8. HMA Analysis Results for I-94 Reconstruction in Berrien County MDOT JN 132824 – Analysis Option 1.

Subgrade Soil Type	Resilient Modulus of Subgrade Soil (M_r) (psi)	BU Cracking (%) at 20 years	Predicted Pavement Design Life (years)
CL	4,400	16.40	33
SC	4,400	16.40	33
SM	5,200	15.84	35
SP-SM	7,000	14.98	42

Table 7.9. Analysis Results for I-94 Reconstruction in Berrien County MDOT JN 132824 – Analysis Options 2a and 2b.

Analysis Option	Subgrade Soil Type	Stabilized Layer Soil Type (added 12" layer)	Michigan Method ($4\times M_r$)		Minnesota Method ($2\times M_r$)		Ohio Cement Method ($4.7\times M_r$)	
			BU Cracking (%) at 20 years	Predicted Pavement Design Life (years)	BU Cracking (%) at 20 years	Predicted Pavement Design Life (years)	BU Cracking (%) at 20 years	Predicted Pavement Design Life (years)
Option 2a	CL	CL	15.21	40	15.87	36	15.20	41
	SC	SC	15.21	40	15.80	36	15.07	41
	SM	SM	14.89	42	15.36	39	14.78	43
	SP-SM	SP-SM	14.06	49	14.49	46	14.06	50
Option 2b	CL	SP-SM	15.21	40	15.80	36	15.07	41
	SC	SP-SM	15.21	40	15.80	36	15.07	41
	SM	SP-SM	14.75	43	15.27	39	14.63	43
	SP-SM	SP-SM	14.06	49	14.49	46	14.06	50

Table 7.10. HMA Analysis Results for I-94 Reconstruction in Berrien County MDOT JN 132824 – Analysis Options 2c and 2d.

Analysis Option	Subgrade Soil Type	Stabilized Layer Soil Type (added 12" layer)	BU Cracking (%) at 20 years	Predicted Pavement Design Life (years)
Option 2c	CL	CL	15.48	39
	SC	SC	15.69	36
	SM	SM	15.41	39
	SP-SM	SP-SM	14.8	43
Option 2d	CL	SP-SM	15.79	36
	SC	SP-SM	15.79	36
	SM	SP-SM	15.4	39
	SP-SM	SP-SM	14.8	43

Table 7.11 provides a summary of predicted pavement design life increases due to subgrade stabilization for analysis Options 2a and 2b, while Table 7.12 provides a summary of predicted

pavement design life increases due to subgrade stabilization for analysis Options 2c and 2d. The increased life is relative to the initial design of the respective subgrade soil type in analysis Option 1.

Table 7.11. HMA Summary Results for I-94 Reconstruction in Berrien County (MDOT JN 132824) for Analysis Options 2a and 2b.

Analysis Option	Subgrade Soil Type	Stabilized Layer Soil Type (added 12" layer)	Predicted Pavement Design Life Increase due to Subgrade Stabilization		
			Michigan Method ($4 \times M_r$)	Minnesota Method ($2 \times M_r$)	Ohio Cement Method ($4.7 \times M_r$)
2a	CL	CL	7	3	8
	SC	SC	7	3	8
	SM	SM	7	4	8
	SP-SM	SP-SM	7	4	8
2b	CL	SP-SM	7	3	8
	SC	SP-SM	7	3	8
	SM	SP-SM	8	4	8
	SP-SM	SP-SM	7	4	8

Table 7.12. HMA Summary Results for I-94 Reconstruction in Berrien County (MDOT JN 132824) for Analysis Options 2c and 2d.

Analysis Option	Subgrade Soil Type	Stabilized layer Soil Type (added 12" layer)	Predicted Pavement Design Life Increase due to Subgrade Stabilization
2c	CL	CL	6
	SC	SC	3
	SM	SM	4
	SP-SM	SP-SM	1
2d	CL	SP-SM	3
	SC	SP-SM	3
	SM	SP-SM	4
	SP-SM	SP-SM	1

The above results are illustrated in Figures 7.3 to 7.5 below for the I-94 Reconstruction Project (MDOT JN 132824) for Michigan, Minnesota, and Ohio methods, respectively.

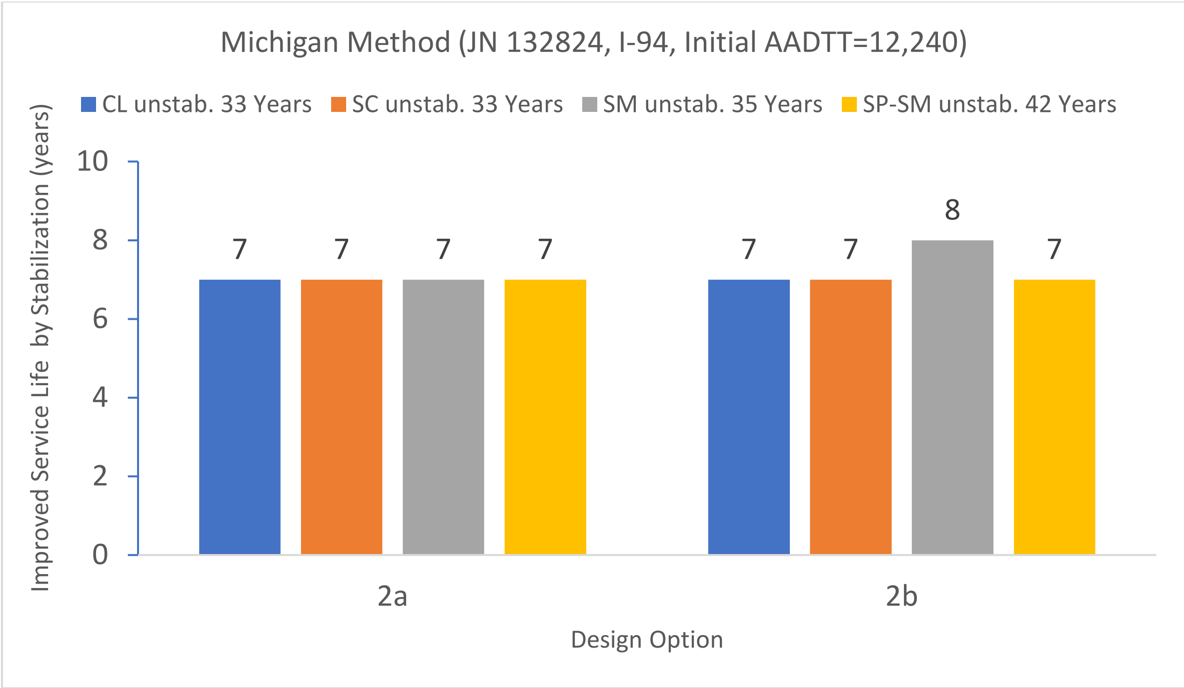

Figure 7.3 AASHTOWare Pavement ME Predicted Pavement Life Increase for Michigan Method for HMA Design, JN 132824.

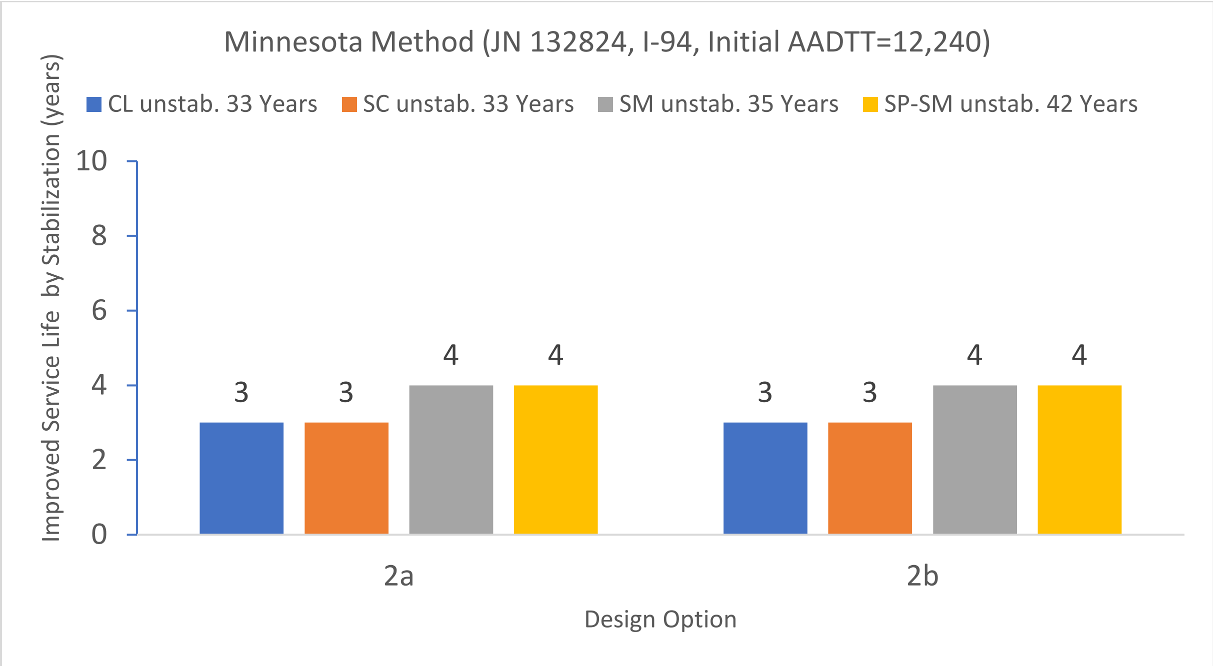

Figure 7.4 AASHTOWare Pavement ME Predicted Pavement Life Increase for Minnesota Method for HMA Design, JN 132824.

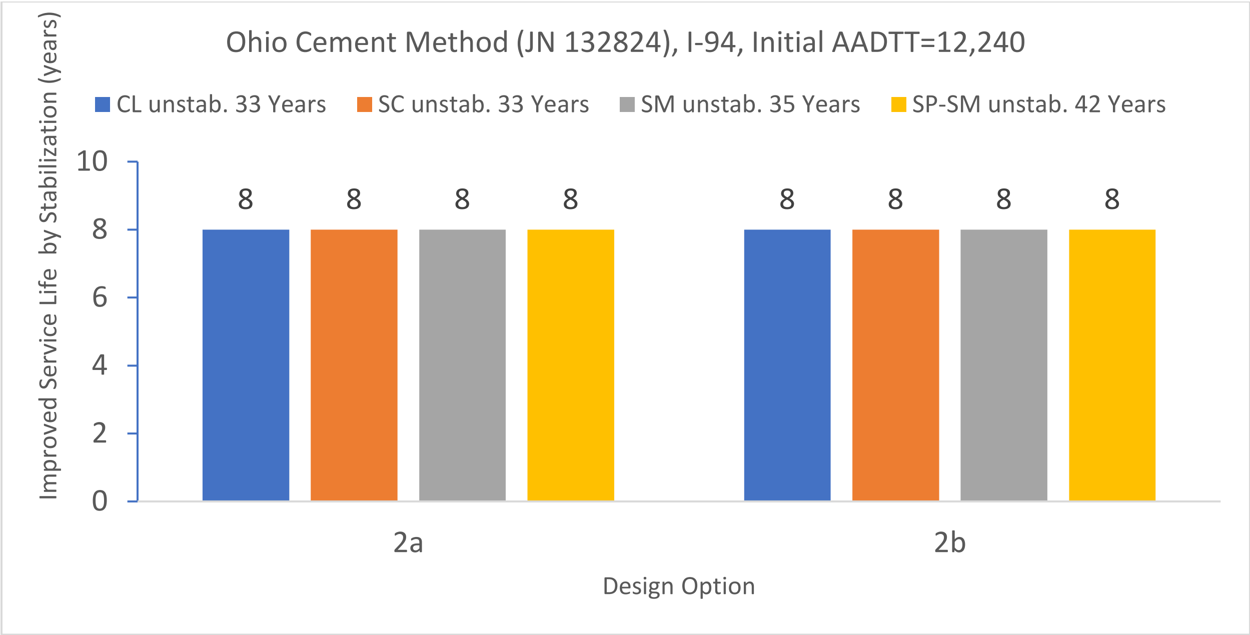

Figure 7.5 AASHTOWare Pavement ME Predicted Pavement Life Increase for Ohio Cement Method for HMA Design, JN 132824.

The results of the analysis Options 2c and 2d are shown in Figure 7.6 below (MDOT JN 132824).

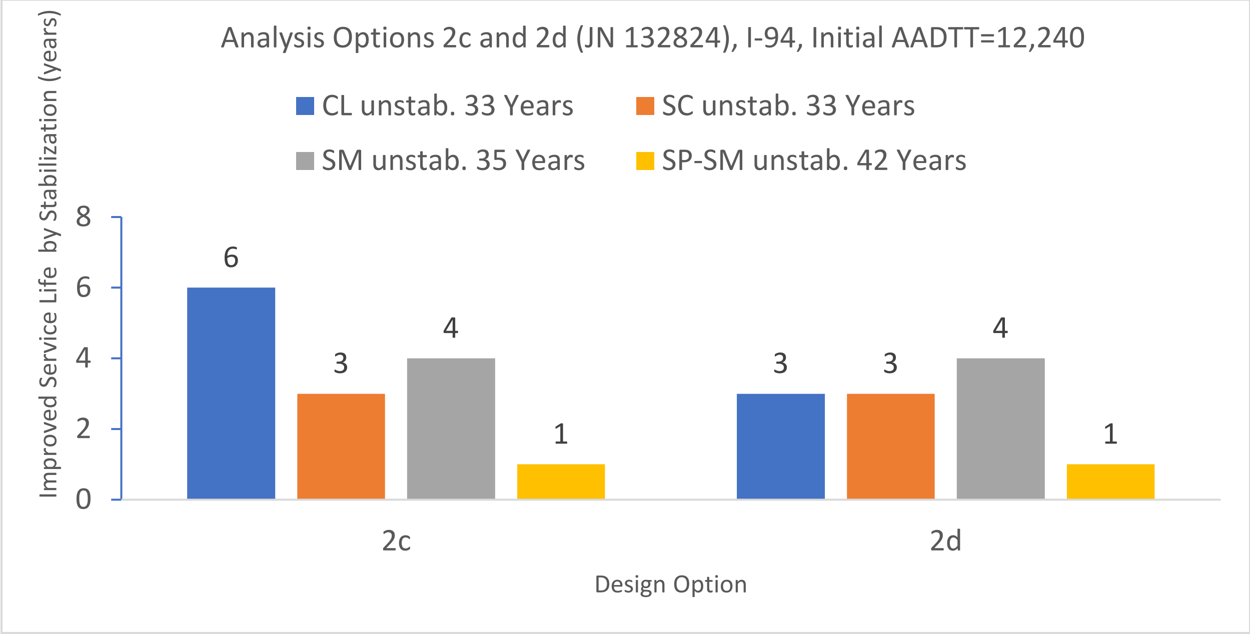

Figure 7.6 AASHTOWare Pavement ME Predicted Pavement Life Increase for Analysis Options 2c and 2d for HMA Design, JN 132824.

As can be seen from Figures 7.3 to 7.6, predicted pavement performance life increases of 1 to 8 years were attained due to stabilization. There was negligible difference in predicted performance life by changing the stabilized layer geotechnical parameters such as gradation, LL, or PI (between analysis Options 2a and 2b). A slight change in predicted performance life was observed when assuming an increased single modulus value for all scenarios of the stabilized layer (Analysis Options 2c and 2d). As previously noted, to estimate the single value to represent the resilient modulus of the stabilized subgrade layer, a minimum CBR value of 20 was used. Still, more research is needed to estimate the appropriate resilient modulus to represent the stabilized layer as these analysis options assess the relative impacts to ME design.

As the resilient modulus of the stabilized layer increased (by using different multipliers), the predicted design life increased, as shown in Figure 7.7 for the I-94 construction project (MDOT JN 132824) as per the results of analysis Option 2a relative to Option 1. The increased predicted design lives plateau around Michigan (4.0) and Ohio (4.7) multipliers, which seems to indicate that higher resilient modulus multipliers are not likely to provide much further increased design life for HMA pavement designs.

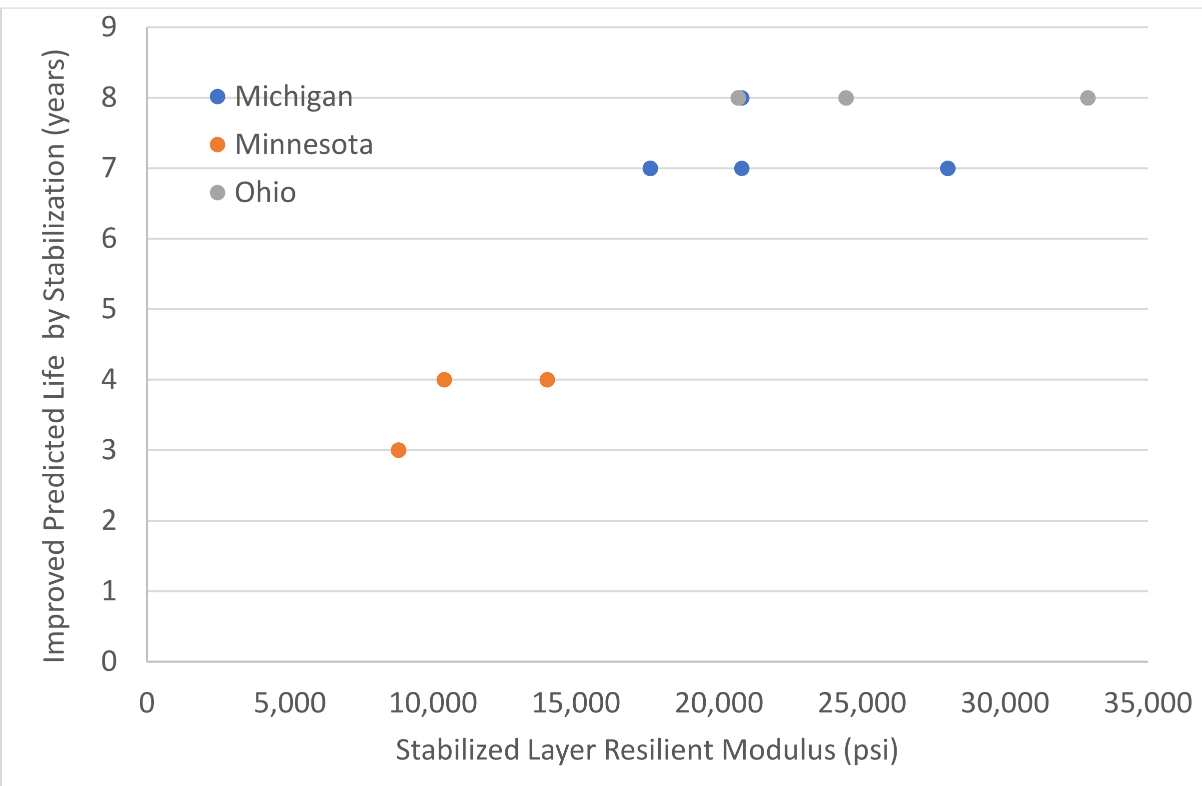

Figure 7.7. JN 132824 Improved Predicted Life due to Stabilization as a function of M_r for HMA Design.

7.5.2 Summary Results for HMA Pavement Analysis of the Other Projects

A similar analysis was performed for the other pavement sections included in the sensitivity analysis. Detailed results are included in Appendix F of this report. Figure 7.8 presents the predicted design life results for 5 of the 6 pavement designs (as previously noted in Table 7.1) with varying traffic levels and in different climatic zones in Michigan. The remaining pavement design for a roadway located in Michigan's upper peninsula (JN203897), with a low traffic level (initial AADTT of 255) did not show similar results as the other 5 pavement designs. See Section 7.5.2.1 for further details.

Figure 7.8 below shows an increase in the predicted design life (when using stabilization) with the increased stabilized layer resilient modulus using different multipliers as per analysis Option 2a relative to Option 1. However, as observed previously, the improved predicted lives plateau around Michigan and Ohio multipliers of 4.0 and 4.7, respectively.

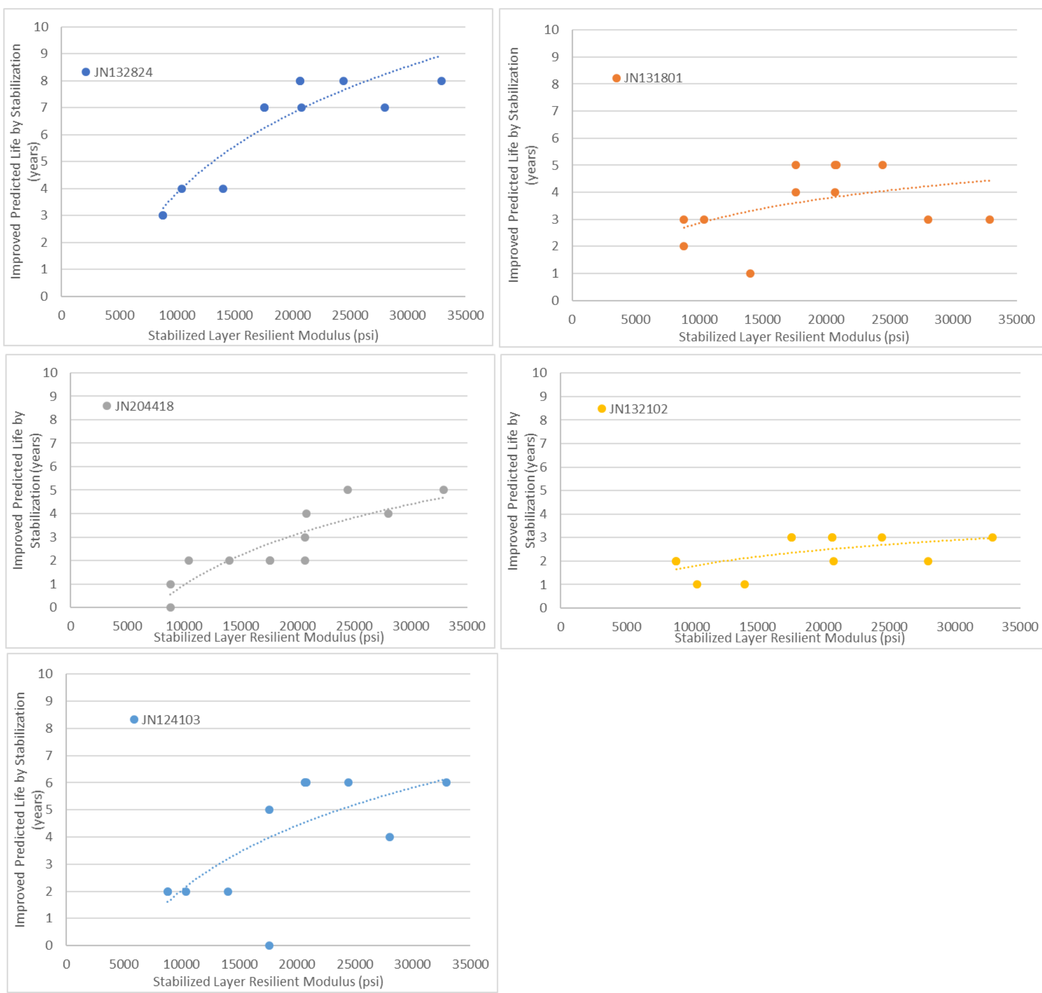

Figure 7.8. Summary of Improved Predicted Life as a Function of M_r for HMA Analysis (for Analysis Option 2a).

7.5.2.1 Analysis Results for JN203897

The AASHTOWare Pavement ME design inputs provided by MDOT for this project are shown in Figure 7.9. As shown in Figure 7.9, the pavement structure consists of 6.5 inches of HMA, followed by 6 inches of dense graded aggregate base, followed by 18 inches of sand subbase over a sandy/silty sand subgrade material. The pavement was designed for 1.0 million cumulative number of heavy trucks over 20 years.

Layer type	Material Type	Thickness (in)
Flexible	5EML_58-34	1.5
Flexible	4EML_58-34	2.0
Flexible	3EML_58-28	3.0
NonStabilized	Agg. Base	6.0
NonStabilized	Sand Subbase	18.0
Subgrade	Poorly Graded Sand/Silty Sand Subgrade	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	12.6
Air voids (%)	6.0

Age (year)	Heavy Trucks (cumulative)
2021 (initial)	255
2031 (10 years)	481,699
2041 (20 years)	1,000,770

Figure 7.9. HMA Pavement Design for US-2 Reconstruction in Iron County (MDOT JN 203897).

The analysis steps provided in Section 7.4 were followed to evaluate the effect of adding a stabilized subgrade layer in the design. The pavement performance life was determined by comparing target distress levels for terminal IRI, pavement deformation – total, AC bottom-up fatigue cracking, AC top-down fatigue cracking, and permanent deformation- AC only. The analysis showed that the pavement designs for every analysis option failed by exceeding the terminal IRI above the target IRI. However, all other five pavement designs were failed by exceeding the bottom-up cracking above the target value. The analysis also showed that the pavement predicted life did not significantly change due to subgrade stabilization as shown in the other designs. These results also showed that when the traffic levels are low and minimum recommended thickness values are used in the pavement design, the benefit of using stabilized subgrade layers is not attained in the predicted pavement life. However, other benefits of subgrade stabilization, such as improved constructability and uniform subgrade throughout the project area, can be expected by introducing subgrade stabilization for low volume roads. Further research is recommended to study the effect of subgrade stabilization for low volume roads.

7.6 AASHTOWare Pavement ME Analysis results for JPCP Designs

The following section provides the input data, initial pavement design used for analysis, and the results of all the analysis options for MDOT project JN 132824, I-94 from Red Arrow Highway to Britain Avenue in Berrien County in the Southwest Region. A similar analysis approach was followed for the other remaining projects, and summary results are included in Section 7.6.2 of this report.

7.6.1 I-94 Reconstruction in Berrien County MDOT JN 132824 JPCP Pavement Design

The AASHTOWare Pavement ME design inputs provided by MDOT for this project are shown in Figure 7.10. As shown in Figure 7.10, the pavement structure consists of 11.5 inches of JPCP, followed by 6 inches of open graded drainage course, followed by a 10 inches of sand subbase over a sandy clay subgrade material. The pavement was designed for 36.6 million cumulative number of heavy trucks for 20 years. The joint spacing and dowel diameter were 14-ft and 1.5-inch, respectively, based on MDOT guidelines given in the *MDOT User Guide for ME Pavement Design.*

Design Structure

Layer type	Material Type	Thickness (in)
PCC	JPCP	11.5
NonStabilized	OGDC	6.0
NonStabilized	Sand Subbase	10.0
Subgrade	Sandy Clay Subgrade	Semi-infinite

Joint Design:	
Joint spacing (ft)	14.0
Dowel diameter (in)	1.50
Slab width (ft)	12.0

Traffic

Age (year)	Heavy Trucks (cumulative)
2023 (initial)	12,240
2033 (10 years)	17,833,200
2043 (20 years)	36,578,300

Figure 7.10. JPCP Pavement Design for I-94 Reconstruction in Berrien County MDOT JN 132824.

Figure 7.11 shows the AASHTOWare Pavement ME predicted performance for the initial (passing) design used for analysis.

Design Outputs

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	164.17	95.00	96.71	Pass
Mean joint faulting (in)	0.13	0.09	95.00	99.40	Pass
JPCP transverse cracking (percent slabs)	15.00	0.68	95.00	100.00	Pass

Figure 7.11. Performance Prediction Indicators for JN 132824 (Option 1 – non-stabilized analysis).

The next step is to follow the analysis steps provided in Section 7.4 to evaluate the effect of adding a stabilized subgrade layer in the design. Table 7.10 shows the JPCP analysis results for I-94 Reconstruction in Berrien County.

The predicted design life of the pavement designs was calculated by running the pavement design for an analysis period of 50 years. Predicted lives for a non-stabilized pavement section and a stabilized pavement section are obtained when one of the predicted distress types (IRI, Mean

Joint Faulting (inches), and JPCP Transverse Cracking (% Slabs)) exceeded the target distress value.

Only minimal changes were observed for mean joint faulting and JPCP transverse cracking performance when a stabilized layer was included in the design. Therefore, only IRI and predicted pavement life are shown in Tables 7.13 to 7.15 for I-94 Reconstruction in Berrien County for Option 1, Options 2a and 2b, and Options 2c and 2d, respectively.

Table 7.13. JPCP Analysis Results for I-94 Reconstruction in Berrien County MDOT JN 132824 – Analysis Option 1.

Subgrade Soil Type	Resilient Modulus of Subgrade Soil (M_r) (psi)	IRI at 20 years (in/mile)	Predicted Pavement Design Life (years)
CL	4,400	170.2	22
SC	4,400	165.7	23
SM	5,200	160.4	26
SP-SM	7,000	152.4	36

Table 7.14. JPCP Analysis Results for I-94 Reconstruction in Berrien County MDOT JN 132824 – Analysis Options 2a and 2b.

Analysis Option	Subgrade Soil Type	Stabilized layer Soil Type (added 12" layer)	Michigan Method ($4 \times M_r$)		Minnesota Method ($2 \times M_r$)		Ohio Cement Method ($4.7 \times M_r$)	
			IRI at 20 Years (in/mile)	Predicted Pavement Design Life (years)	IRI at 20 Years (in/mile)	Predicted Pavement Design Life (years)	IRI at 20 Years (in/mile)	Predicted Pavement Design Life (years)
Option 2a	CL	CL	165.4	23	166.0	23	165.2	23
	SC	SC	164.4	23	165.0	23	164,2	24
	SM	SM	159.0	27	159.6	26	158.9	27
	SP-SM	SP-SM	151.4	36	151.8	36	151.3	36
Option 2b	CL	SP-SM	153.9	33	154.4	32	153.8	33
	SC	SP-SM	153.9	32	154.4	33	153.8	34
	SM	SP-SM	152.9	35	153.4	34	152.8	36
	SP-SM	SP-SM	151.4	36	151.8	36	151.3	36

Table 7.15. Analysis Results for I-94 Reconstruction in Berrien County MDOT JN 132824 – Analysis Options 2c and 2d.

Analysis Option	Subgrade Soil Type	Stabilized layer Soil Type (added 12" layer)	IRI at 20 Years (in/mile)	Predicted Pavement Design Life (years)
Option 2c	CL	CL	165.6	24
	SC	SC	164.9	23
	SM	SM	159.7	27
	SP-SM	SP-SM	152.1	36
Option 2d	CL	SP-SM	154.4	33
	SC	SP-SM	154.4	33
	SM	SP-SM	153.5	33

Analysis Option	Subgrade Soil Type	Stabilized layer Soil Type (added 12" layer)	IRI at 20 Years (in/mile)	Predicted Pavement Design Life (years)
	SP-SM	SP-SM	152.1	36

Table 7.16 provides a summary of the increase in predicted pavement design life due to subgrade stabilization for analysis Options 2a and 2b, while Table 7.17 provides a summary of the increase in predicted pavement design life due to subgrade stabilization for analysis Options 2c and 2d. The increased life is calculated relative to the resulting design life of the corresponding subgrade soil type in analysis Option 1.

Table 7.16. Summary Results for I-94 JPCP Reconstruction in Berrien County (MDOT JN 132824) for Analysis Options 2a and 2b.

Analysis Option	Subgrade Soil Type	Stabilized layer Soil Type (added 12" layer)	Predicted Pavement Design Life Increase due to Subgrade Stabilization		
			Michigan Method ($4 \times M_r$)	Minnesota Method ($2 \times M_r$)	Ohio Cement Method ($4.7 \times M_r$)
2a	CL	CL	1	1	1
	SC	SC	0	0	1
	SM	SM	1	0	1
	SP-SM	SP-SM	0	0	0
2b	CL	SP-SM	11	10	11
	SC	SP-SM	9	10	11
	SM	SP-SM	9	8	10
	SP-SM	SP-SM	0	0	0

Table 7.17. Summary Results for I-94 JPCP Reconstruction in Berrien County (MDOT JN 132824) for Analysis Options 2c and 2d.

Analysis Option	Subgrade Soil Type	Stabilized layer Soil Type (added 12" layer)	Predicted Pavement Design Life Increase due to Subgrade Stabilization
2c	CL	CL	2
	SC	SC	0
	SM	SM	1
	SP-SM	SP-SM	0
2d	CL	SP-SM	11
	SC	SP-SM	10
	SM	SP-SM	9
	SP-SM	SP-SM	0

The above results are illustrated in Figures 7.12 to 7.14 below for the I-94 Reconstruction Project (MDOT JN 132824) for Michigan, Minnesota, and Ohio methods, respectively.

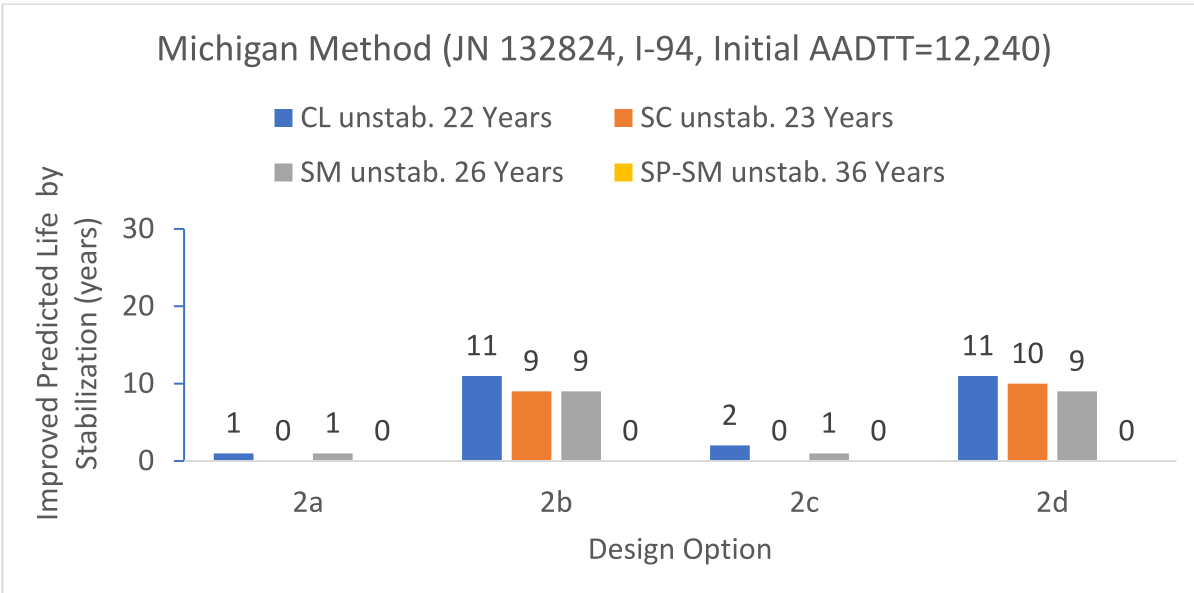

Figure 7.12 AASHTOWare Pavement ME Predicted Pavement Life Increase for Michigan Method for JPCP Design, JN 132824.

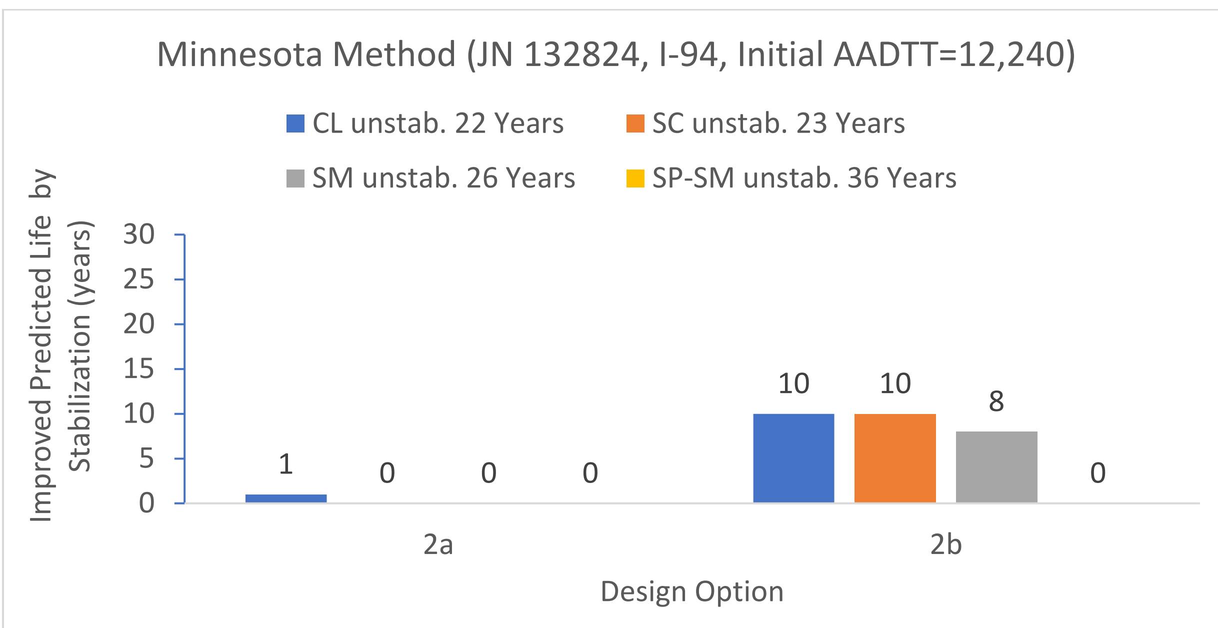

Figure 7.13 AASHTOWare Pavement ME Predicted Pavement Life Increase for Minnesota Method for JPCP Design, JN 132824.

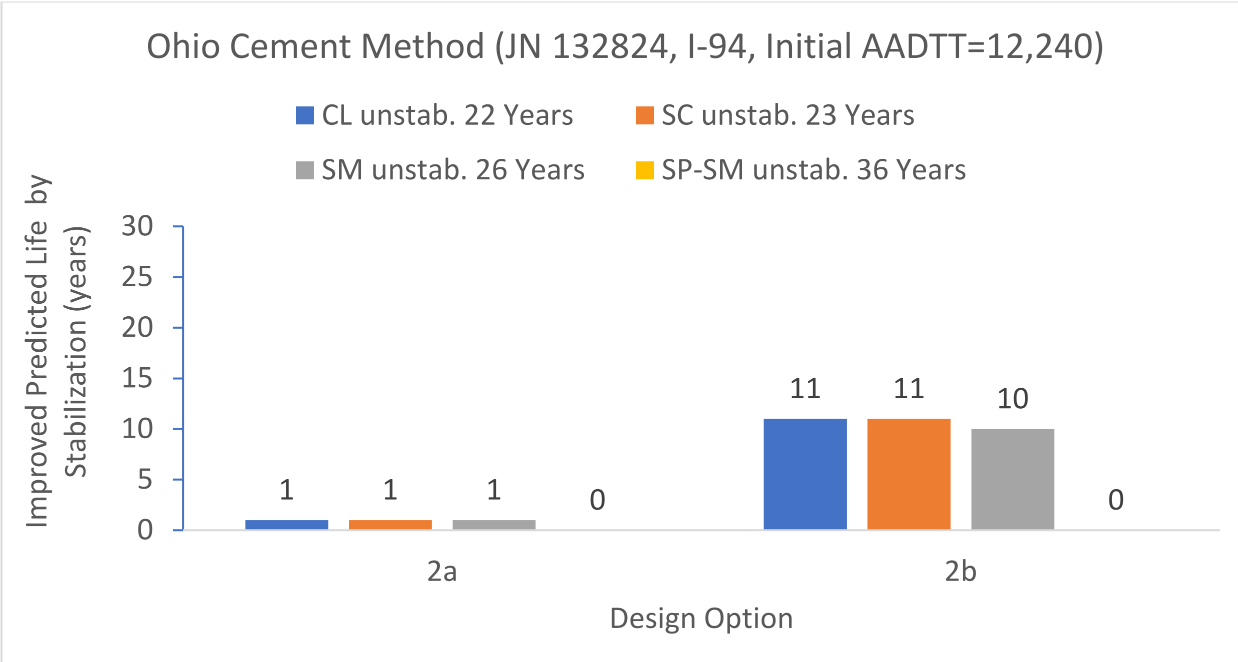

Figure 7.14 AASHTOWare Pavement ME Predicted Pavement Life Increase for Ohio Cement Method for JPCP Design, JN 132824.

As seen from Figures 7.12 to 7.14, the predicted pavement performance life increase for rigid pavement design was marginal for design Options 2a and 2c (increasing stabilized layer moduli without changing the geotechnical parameters), ranging from 0-1 years. However, for design Options 2b and 2d (increasing the stabilized layer moduli with changing the geotechnical parameters), the improved predicted life ranged from 8-11 years for all subgrade soil types except SP-SM soil types (since the SP-SM subgrade type was not changed). This is a distinct difference from HMA pavement designs.

Both faulting and IRI prediction equations in AASHTOWare Pavement ME contain percentage passing #200 sieve (P_{200}) as an input variable. When the stabilized layer geotechnical properties were changed to the SP-SM soil type, as in Options 2b and 2d, the P_{200} value was changed. Therefore, due to this change, the resulting predicted lives were improved.

7.6.2 Summary Results for Other Projects

Similar results were obtained for the other pavement design projects. Since there is no change in the pavement life improvement, no graphical representation is included. A summary of the obtained results is included in Appendix F of this report.

7.7 Summary of Pavement Design Results

The following section summarizes the pavement design results for both HMA pavement and JPCP obtained from the AASHTOWare Pavement ME software. Include some in terms of the analysis was based on inbuilt models and not specifically developed for stabilized layers.

7.7.1 Summary of HMA Pavement Analysis

1. The pavement's predicted performance design life increased by 1-8 years due to including subgrade stabilization with modification to its modulus value in the design.
2. Predicted design life also increased when assuming a single minimum CBR value of 20 as correlated to a modulus value (with ME EICM) for the stabilized layer.
3. The increase in predicted design life is mainly due to a reduction in bottom-up cracking (fatigue cracking) due to better support provided by the stabilized layer per the increased resilient modulus.
4. Almost no change in predicted design life was observed by changing the stabilized layer geotechnical parameters such as gradation, LL, PI, etc.

7.7.2 Summary of JPCP Pavement Analysis

1. The pavement's predicted performance design life is unchanged or minimally increases by 1-2 years due to including subgrade stabilization with modification to its modulus value in the design.
2. The pavement's predicted performance design life increased by 8-11 years due to changes in the stabilized layer geotechnical parameters such as gradation, LL, PI, etc.
3. Rigid pavement performance design life is greatly affected by changes in P_{200} value.

7.7.3 Recommendations for Pavement Design Inputs

The following recommendations are developed based on the AASHTOWare Pavement ME analysis conducted during this research.

1. Continue using the current MDOT practice of a multiplier of 4 for the stabilized layer without changing the other geotechnical parameters as this was found to be reasonable per the sensitivity analyses conducted in this research. The geotechnical parameters, such as P_{200} value of the stabilized layer, greatly influence the performance prediction of JPCP pavements but do not affect the performance prediction for HMA pavements. Therefore, without conducting further research, only the resilient modulus increase is recommended for the stabilized subgrade.

2. More research is needed to study the change in geotechnical parameters of the stabilized layer for pavement design. This work is particularly needed to validate how subgrade stabilization may impact rigid pavement performance.

3. More research is needed to establish the resilient modulus of the stabilized layer. The analyses were conducted using multipliers of the subgrade resilient modulus or a minimum recommended CBR of 20 for the stabilized subgrade layer. More research based on the long-term evaluation of pavement construction projects with stabilized subgrades is warranted to estimate the resilient modulus of the stabilized layer.

CHAPTER 8 FINDINGS AND RECOMMENDATIONS

Based on the data and results presented in the previous chapters, a series of conclusions and recommendations were developed.

8.1 Findings

Key findings from this research include the following:

- Based on the results of the literature review, survey of other state practices, and interviews with MDOT and consulting staff experienced in subgrade stabilization, subgrade stabilization was found to be widely used in select states. In those states, well-established guidance documents and specifications for construction of stabilized subgrades were often available.
- Subgrade treatment can be divided into two separate categories: modification and stabilization.
  - If the goal of the treatment is to stabilize areas with problematic soils encountered during construction, this practice is commonly referred to as *subgrade modification.* The goal of subgrade modification is to construct a stable platform to facilitate the construction of upper pavement layers.
  - If the goal of the treatment is to construct a long-lasting stable layer above the natural subgrade, this practice is referred to as s*ubgrade stabilization*. If proper mix design and construction procedures are followed, pavement design inputs for the stabilized layer can be modified, likely leading to enhanced pavement performance predictions.
- The most common subgrade stabilization materials included cement and lime. However, other stabilizers such as Class C fly ash and recycled materials such as CKD and LKD have been successfully used in some states.
- During a pavement construction project's scoping and design phase, well-planned geotechnical exploration and testing procedures should be followed to evaluate roadway construction projects for potential subgrade stabilization. If proper geotechnical evaluations and testing procedures are followed, costly project modifications during construction can be avoided as a result of variable conditions.
- Mix design procedures to establish proper stabilizer percentages based on the subgrade soil type should be followed. Different procedures and testing requirements exist for different stabilizer types. Subgrade stabilization processes should be altered or avoided if high-organic or high-sulfate soils are encountered during the initial geotechnical investigation.

- Properly established construction procedures, with proper quality control and quality assurance procedures during stabilized subgrade construction, are important to obtain long lasting stabilized subgrade layers.
- The survey of state DOT personnel indicated that some state DOTs have established input parameters for stabilized layers in pavement design. Most state DOTs have established structural layer coefficients for stabilized subgrade layers based on AASHTO's *Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials, 1993) procedures. A few state DOTs have input value guidelines for stabilized subgrades in the AASHTOWare Pavement ME Design software; a subgrade layer with a higher resilient modulus was recommended by all state DOTs using the AASHTOWare Pavement ME Design software.
- Analysis of a pavement system with a 12-inch subgrade stabilized layer using the AASHTOWare Pavement ME Design software predicted bottom-up cracking performance improvements for flexible pavements due to their increased resilient modulus value. The highest improvement was noted for subgrades with high clay contents. The performance improvements for rigid pavements with a 12-inch stabilized subgrade layer were also observed but were minimal.

8.2 Recommendations and Implementation

A series of recommendations and implementation techniques were derived from the results of the literature review as well as other investigations completed as part of this study.

8.2.1 Recommendations Regarding Project Evaluation for Stabilized Subgrades

Researchers recommend following the project selection guidance document developed during this study (included in Appendix B) to evaluate project sites for subgrade stabilization. The project selection guidance document recommends geotechnical investigations and testing procedures to evaluate potential sites during a project's scoping and design phase. The following conditions may warrant subgrade stabilization:

- Reconstruction or new construction projects.
- Projects where the pavement surface component cost exceeds $1.5 million.
- Projects situated in glacial lakebed clay subgrade regions of the State.
- Existing clayey embankment fill areas.
- Weak clayey subgrade areas near peat marsh deposits and river beds.

For projects that may warrant subgrade stabilization, the following geotechnical investigation tools are recommended to further confirm the suitability of the project for subgrade stabilization:

- United States Department of Agriculture soil survey (Web Soil Survey site).
- Geologic and topographical map reviews.
- Falling weight deflectometer testing.
- Ground penetrating radar testing.
- Dynamic cone penetrometer testing.
- Preliminary soil boring information.
- Preliminary drainage survey for existing pavements.

The project selection guidance document provides recommendations for the minimum recommended frequencies of the geotechnical investigations and other geotechnical testing. The project selection guidance document also provides decision trees to aid in selecting preliminary stabilizer types based on the subgrade properties.

8.2.2 Recommendations Regarding Mix Designs for Stabilized Subgrades

Researchers recommend following the mix design guidance document developed during this project (included in Appendix C) to determine stabilizer types and percentages based on the geotechnical investigation results for each stabilization project. The mix design guidance document briefly describes the chemical stabilization mechanism and provides recommendations for the following:

- Soil sampling.
- Basic material testing.
- Additive selection and mix design.
  - Mix design for lime stabilization.
  - Mix design for cement stabilization.
  - Mix designs for lime-fly ash and lime-cement dual treatments.
- Mix design reports.
- Materials.

8.2.3 Recommendations Regarding Construction of Stabilized Subgrades

A comprehensive guide for the construction of stabilized subgrades was also developed during this project (included in Appendix D). The intent of this resource was to aid MDOT staff and consultants in properly directing and inspecting stabilized subgrade work during construction. Following a general description, this guidance document provides recommendations for the following:

- Materials.
- Equipment.

- Preconstruction.
- Construction of stabilized subgrades.
- Inspection and testing.
- Measurement, documentation, and payment.

A checklist for test strip construction and a summary of construction procedures are also included in the appendices of this guidance document. The checklist can be used by MDOT construction staff to document the test strip construction process. Proper construction of the test strip during construction of the stabilized subgrade is important for achieving long lasting results.

8.2.4 Special Provision for Construction of Chemically Stabilized Subgrade

A special provision for the construction of stabilized subgrades was developed in this study and is included in Appendix E of this report. This SP applies to lime, cement, lime-fly ash, and lime-cement subgrade treatment. This draft SP should be considered for implementation by MDOT in future subgrade stabilization projects.

8.2.5 Pavement Design Inputs for Stabilized Subgrade Layers

A limited sensitivity analysis of the geotechnical inputs for the stabilized layers was conducted using the AASHTOWare Pavement ME Design software. Researchers recommend following the current MDOT practice of using a stabilized subgrade resilient modulus that is four times the in situ subgrade modulus until more comprehensive laboratory and field evaluations of the stabilized layer modulus are conducted. This analysis showed improved performance in pavement designs using stabilized subgrades with flexible pavements. However, rigid pavements showed minimal performance improvements in pavement designs using stabilized subgrades. This finding is logical because rigid pavements are inherently less impacted by their base and subbase layer thicknesses or stiffness. However, this may warrant future investigation as constructability improvement may further impact long term performance results. Additionally, the geotechnical parameters such as P_{200} value of the stabilized layer greatly influence the performance prediction of JPCP pavements but do not affect the performance prediction for HMA pavements. Therefore, without conducting further research, only the resilient modulus increase is recommended for the stabilized subgrade.

8.3 Recommendations for Future Work

Recommendations for future work based on this research include the following:

- For future subgrade stabilization projects, use the developed special provision for construction and document experiences including quality control and quality assurance test results. Use the practical experiences to refine the special provision.

- Perform a comprehensive field performance review such as cracking and IRI of projects that have included subgrade stabilization in Michigan. Collect performance data and to assess the need for calibration of performance models for stabilized layers.
- Field validate the pavement structural design assumptions such as stabilized layer resilient modulus when using stabilized subgrade in Michigan using tools such as the FWD and rapid travel profiler

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APPENDIX A: COPIES OF DEPLOYED SURVEYS

Survey on Subgrade Stabilization in Michigan

Survey on Subgrade Stabilization in Michigan

Lawrence Technological University is conducting a research project for the Michigan Department of Transportation (MDOT) to establish policies and procedures for use of subgrade stabilization in Michigan.

You have been identified as one of the MDOT staff members who has worked on previous subgrade stabilization projects constructed in Michigan. Based on your experience in the past subgrade stabilization projects, please answer the following questions.

1. Your Contact Details

Name:

Title:

Phone Number:

E-mail Address:

2. Project Numbers and Locations of Past Subgrade Stabilization Projects

Project No/Location:

Project No/Location:

Project No/Location:

3. How was the stabilizer type and rate selected?

- Specified in the construction specification
- Contractor designed

Other (please specify)

4. Is a mix design summary available? If Yes, please provide a copy of the mix design summary.

- No
- Yes

5. If a mix design summary available, please upload a copy of the specification here.

Choose File Choose File No file chosen

6. What went well, and what concerns existed, during construction?

7. Were there any issues with the additional testing burden required for developing a mix design, constructing, inspecting, and accepting a stabilized subgrade layer? (please describe)

8. Please share any lessons learned and other details not related to the above questions

Survey on Subgrade Stabilization for Roadway Construction

Survey on Subgrade Stabilization for Roadway Construction

Lawrence Technological University is conducting a research project for Michigan Department of Transportation (MDOT) to establish policies and procedures for use of subgrade stabilization in Michigan.
You have been identified as one of the staff members who has worked on previous subgrade stabilization projects constructed in your state. Based on your experience in the past subgrade stabilization projects, please answer the following questions.

1. Your Contact Details

Name:

Title:

Phone Number:

E-mail Address:

2. Project Numbers and Locations of Past Subgrade Stabilization Projects

Project No/Location:

Project No/Location:

Project No/Location:

3. Please explain your agency's experience in subgrade stabilization.

- ◯ None
- ◯ Very Little (Less than 5 projects)
- ◯ Some (5 to 10 projects)
- ◯ A lot (more than 10 projects)

4. What are the main treatment materials used for subgrade stabilization/modification?

- ☐ Cement
- ☐ Lime
- ☐ Fly Ash
- ☐ Lime+Fly Ash
- ☐ Other (please specify)

5. How do you select a project for subgrade stabilization?

- ☐ Standard specification
- ☐ Standard operating procedure
- ☐ Other (please specify)

6. Do you use cost-benefit analysis for project selection?

- ○ Yes
- ○ No

7. If you use cost-benefit analysis, please briefly describe it here.

8. What is the main goal of the subgrade treatment?

- ○ Long term stabilization
- ○ Modification for a construction platform
- ○ Other (please specify)

9. Does your State have specifications for mix design?

- ○ Yes
- ○ No

10. If your State has specifications for mix design, please upload it here

Choose File Choose File No file chosen

11. Does your State have construction specifications for subgrade stabilization?

- ◯ Yes
- ◯ No

12. If your State has construction specifications for subgrade stabilization, please upload your specification here.

Choose File Choose File No file chosen

13. What is the method of construction acceptance for stabilized subgrades? (Please check all that apply)

- ☐ Density
- ☐ Moisture Content
- ☐ Depth of Treatment
- ☐ Deflection
- ☐ Stiffness of Modulus
- ☐ Intelligent Compaction
- ☐ Other (please specify)

14. Does your State use stabilized subgrade properties in the pavement design process? if so, please share how the stabilized subgrade properties are accounted for in the pavement design?

15. Does your State address potential changes in the permeability of the treated subgrade in planning pavement drainage? If so, how?

16. If underdrains are also included in the project, how and when are they installed relative to the stabilization process?

17. Please share any lessons learned and other details not related to the above questions

18. Were there any issues with the additional testing burden required for developing a mix design, constructing, inspecting, and accepting a stabilized subgrade layer? (please describe)

19. Please share any files not related to the above questions.

Choose File Choose File No file chosen

20. Please share the contact details for the contractors and consultants involved in subgrade stabilization in your state?

Contact Details:

Contact Details:

Contact Details:

Contact Details:

Contact Details:

APPENDIX B: TECHNICAL GUIDE FOR SELECTION OF PAVEMENT PROJECTS FOR CHEMICAL STABILIZATION OF SUBGRADE SOILS

Technical Guide
Selection of Pavement Projects for Chemical Stabilization of Subgrade Soils

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INTRODUCTION

The Michigan Department of Transportation (MDOT) possesses experience with constructing a limited number of projects utilizing subgrade stabilization. To promote the appropriate use of subgrade stabilization, this technical guide provides guidance to aid the designer in determining how to properly scope a project to determine suitability for subgrade stabilization. These guidelines include sampling, subgrade characterization tests and methods, and initial selection of suitable stabilizer.

The information in this guide applies to new construction and reconstruction of existing roadways. This guide draws on several existing MDOT documents, which include but are not limited to the following:

- MDOT *Geotechnical Manual*.
- MDOT *2020 Standard Specifications for Construction*.
- *Manual for the Michigan Test Methods (MTM)*.
- MDOT *Pavement Selection Manual*.
- MDOT *User Guide for Mechanistic-Empirical Pavement Design, Interim Edition*.
- MDOT *Road Design Manual*.
- MDOT *Project Scoping Manual*.
- *American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures*, 1993.

Definitions and Terms

The terms “stabilization” and “modification” are often used in this document.

Subgrade stabilization: Long-term strengthening of subgrade soils to improve the uniformity, strength, and durability of the pavement structure. Subgrade stabilization is included in the construction documents and the performance improvement through stabilization is considered in the pavement design methodology.

Subgrade modification: Short-term improvement of pavement subgrade soils to facilitate construction of the pavement structure. Generally, subgrade modification is not included in the construction documents, and this work item is generally requested by contractors during the construction phase of the project due to unexpected poor subgrade conditions. These improvements generally include improved workability, limiting deflection under heavy wheel loads to support construction traffic, and drying action. The pavement design methodology should not consider any subgrade performance improvements due to the modification.

Guidelines for Project Selection for Stabilization

The following conditions warrant exploring subgrade stabilization.

1. Reconstruction or new construction projects.
2. Projects where the pavement surface component cost exceeds $1.5 million.

For projects that warrant exploring subgrade stabilization, the project selection for subgrade stabilization should be considered during the design phase and roadway geotechnical investigation. The selection for subgrade stabilization can be achieved by collecting at least some of the following subgrade and pavement information during project scoping or design:

- United States Department of Agriculture (USDA) soil survey.
- Falling weight deflectometer (FWD) testing.
- Ground penetrometer radar (GPR) testing.
- Dynamic cone penetrometer (DCP) testing.
- Preliminary soil boring information.
- Preliminary drainage survey for existing pavements.

Following these guidelines will provide efficient and cost-effective field investigation practices. Details of the field investigation guidelines are provided in the following section.

FIELD INVESTIGATION GUIDELINES

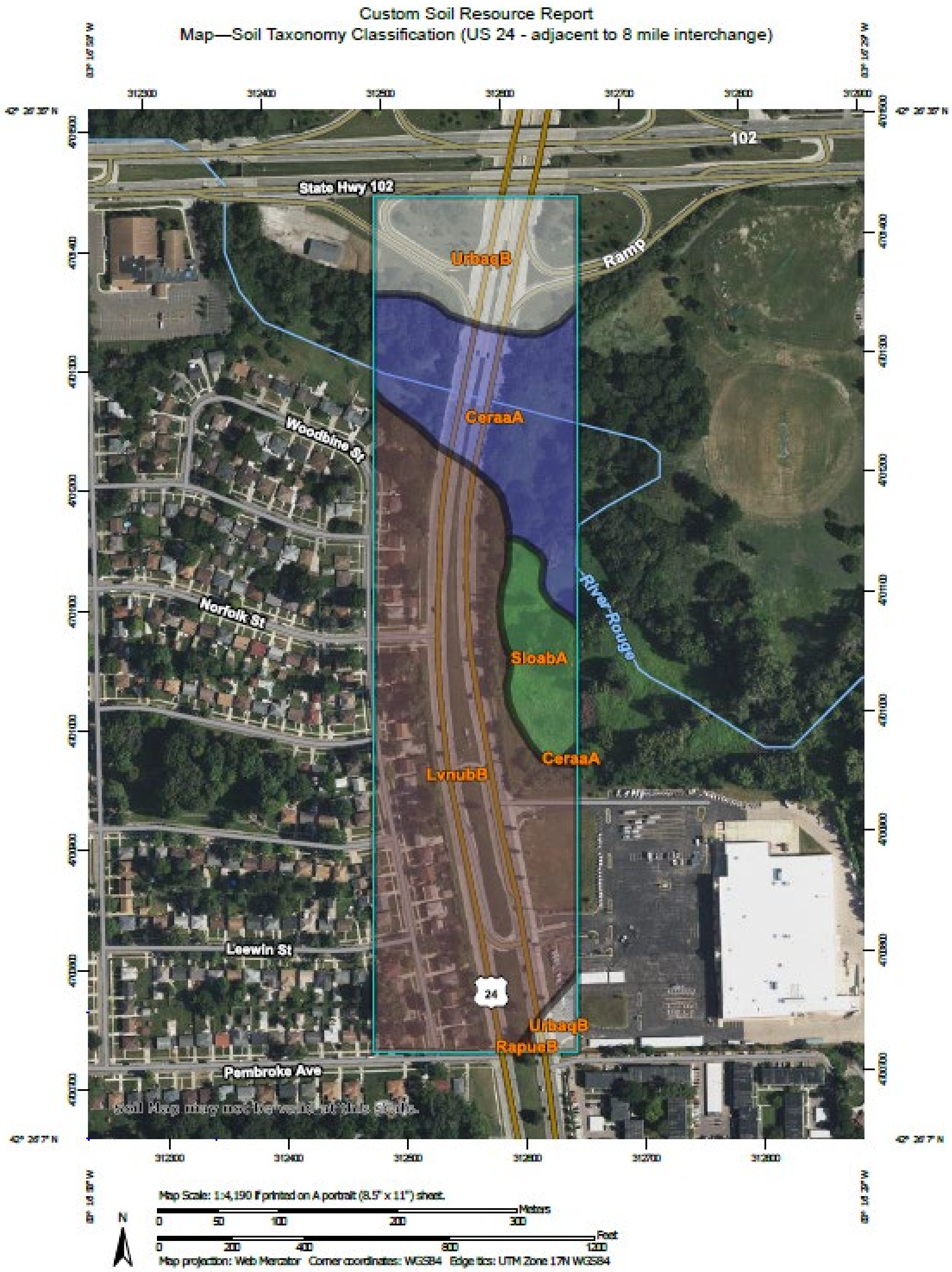
USDA Soil Survey

Obtaining intended in-situ subgrade material properties is the initial step in determining if a subgrade is adequate for the long-term performance of the pavement or if, alternatively, a subgrade is suitable for stabilization to reach adequate long-term performance. Section 5.1 of the MDOT *Geotechnical Manual* outlines details for review of existing data and sources and methods to conduct site reconnaissance. One such data source is the USDA soil survey to aid in the selection of sample locations (https://websoilsurvey.nrcs.usda.gov/). A survey view from a Custom Soil Resource Report for US-24 in Wayne County, Michigan, is shown as an example in Figure 1. The map legends can be found in Figure 2. Engineering soil properties are available for areas identified in the area of interest such as the Livonia-Urban land complex with dense substratum and 0 to 4 percent slopes (see Figure 3). Detailed information can be obtained from the Custom Soil Resource Report about parameters such as:

- Section breaks in soil type.
- Soil profiles.
- AASHTO classification, expected representative percent passing, and Atterberg limits.
- Expected gypsum and organic matter.
- Hydrologic group(s) of the expected soils present within the project extents.
- Ground water table.

Information about the location of the ground water table and approximate hydraulic conductivity can also be used for informational purposes.

There are certain limitations of subsurface information obtained from the USDA soil surveys in urban areas and in the vicinity of major roadways. Due to the original road construction or urban infrastructure expansions, the original shallow soils may have been altered or completely replaced with other types of soils.



Source: https://websoilsurvey.nrcs.usda.gov/

Figure 1. Example view from custom soil resource report for Wayne County, Michigan.

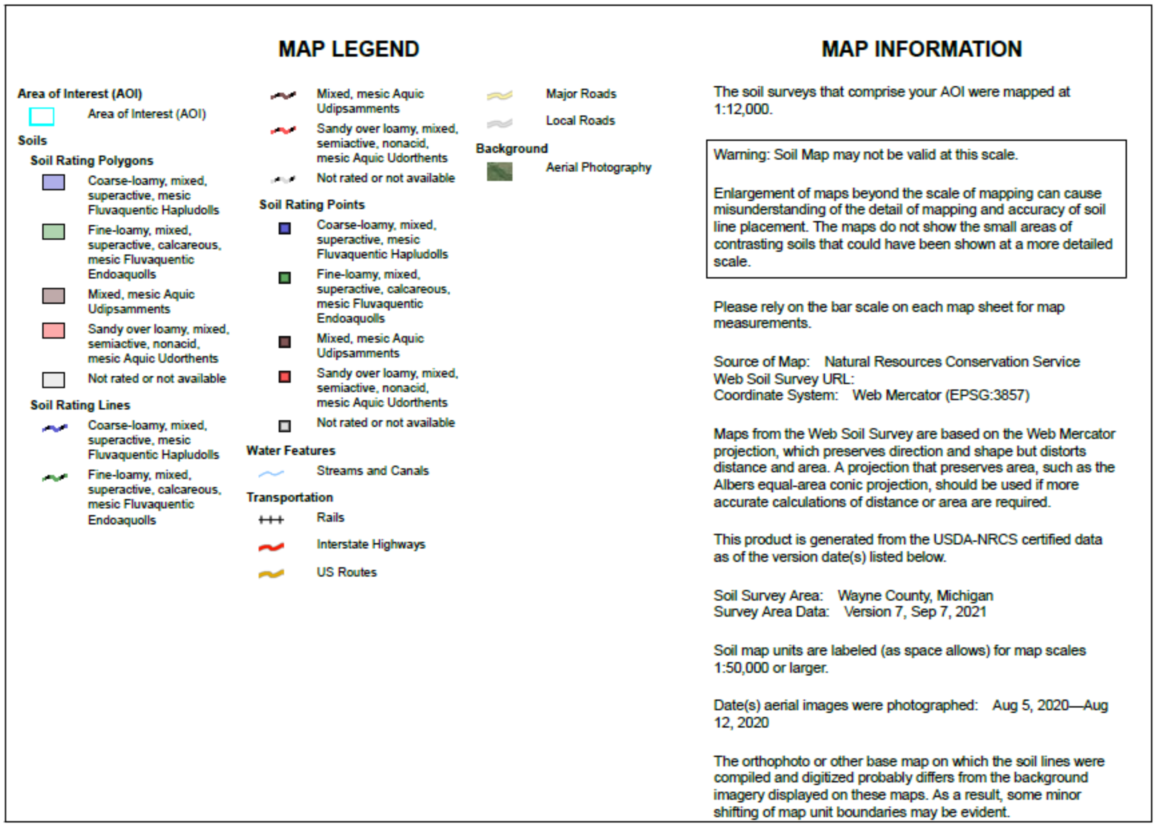


Figure 2. Map legend for custom soil resource report for Wayne County, Michigan.

Engineering Properties–Wayne County, Michigan

Map unit symbol and soil name	Pct. of map unit	Hydrologic group	Depth	USDA texture	Classification		Pct Fragments		Percentage passing sieve number—				Liquid limit	Plasticity index
					Unified	AASHTO	>10 inches	3-10 inches	4	10	40	200		
			In				*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*
LvnubB—Livonia-Urban land complex, dense substratum, 0 to 4 percent slopes														
Livonia, human transported surface	55	C	0-9	Sandy loam	SM	A-1-b, A-2-4, A-4	0- 0- 0	0- 0- 0	77-96-100	73-96-100	50-70-87	13-24-39	0-0 -0	NP
			9-12	Loamy sand, loamy fine sand, sandy loam, loam	SP-SM, ML, SC, SM	A-1-b, A-2-4, A-2-6, A-3, A-4, A-6	0- 0- 0	0- 0- 0	84-94-99	75-92-99	44-73-97	10-26-65	0-19 -35	NP-8 -15
			12-19	Loamy sand, fine sand, sand	SP-SM, SM, SP	A-2-4, A-3	0- 0- 0	0- 0- 0	96-100-100	94-100-100	68-87-94	2-24- 29	0-0 -0	NP
			19-35	Sand, fine sand	SP-SM, SM, SP	A-2-4, A-3	0- 0- 0	0- 0- 0	97-100-100	95-100-100	68-84-90	2-10- 20	0-0 -0	NP
			35-54	Sand, fine sand	SP-SM, SM, SP	A-2-4, A-3	0- 0- 0	0- 0- 0	95-100-100	92-100-100	64-79-90	0- 3- 13	0-0 -0	NP
			54-62	Silty clay loam, silt loam	CL-ML, CL, ML	A-4, A-6	0- 0- 0	0- 0- 0	100-100-100	100-100-100	79-99-100	58-89-96	20-31-40	3-11-18
			62-80	Silty clay, clay loam, clay	CH, CL, MH, ML	A-6, A-7-5, A-7-6	0- 0- 0	0- 0- 0	92-98-100	86-94-99	74-90-99	51-82-97	35-49-66	15-20-27
Urban land	35	D	0-6		—	—	—	—	—	—	—	—	—	—

Source: https://websoilsurvey.nrcs.usda.gov/

Figure 3. Example engineering properties from the custom soil resource report for Wayne County, Michigan.

In Figure 3, three values are provided to identify the expected Low (L), Representative Value (R), and High (H). The hydrologic group example, Group C soils, have a slow infiltration rate when thoroughly wet. These consist chiefly of soils with a layer that impedes the downward movement of water or soils of moderately fine texture. These soils have a slow rate of water transmission.

The information obtained from the USDA soil survey will be used in determining soil sample spacing.

Falling Weight Deflectometer Testing

The FWD is a nondestructive test that simulates a truck wheel loading and measures the pavement response (deflections) to help evaluate the structural capacity of the pavement. Collect FWD data at 0.1-mi spacing unless otherwise directed by MDOT standard operating procedures. Use the FWD to aid in evaluating the subgrade condition in accordance with approved MDOT methods. These methods may include but are not necessarily limited to analysis of the actual deflection measurements and backcalculation of layer modulus values. When performing moduli backcalculations, use existing pavement layer thicknesses that accurately reflect actual site conditions. While historical plans can serve as a starting point, actual field measurements from project scoping and sampling (such as coring, boring, GPR, and DCP results) should be used to verify the existing pavement layer thickness input values. Current MDOT practice of analyzing FWD data can be obtained from MDOT Construction Field Services.

Evaluate the FWD data to determine (a) if the project needs segmentation and (b) if any of the project segments potentially need subgrade stabilization. Figure 4 illustrates FWD results that show a clear section break in subgrade modulus, meaning the project may require segmentation for analysis and design. The results in Figure 4 also suggest a large portion of the project extent exhibits low subgrade modulus values and may justify subgrade stabilization. Table 2 defines the threshold for low subgrade modulus values.

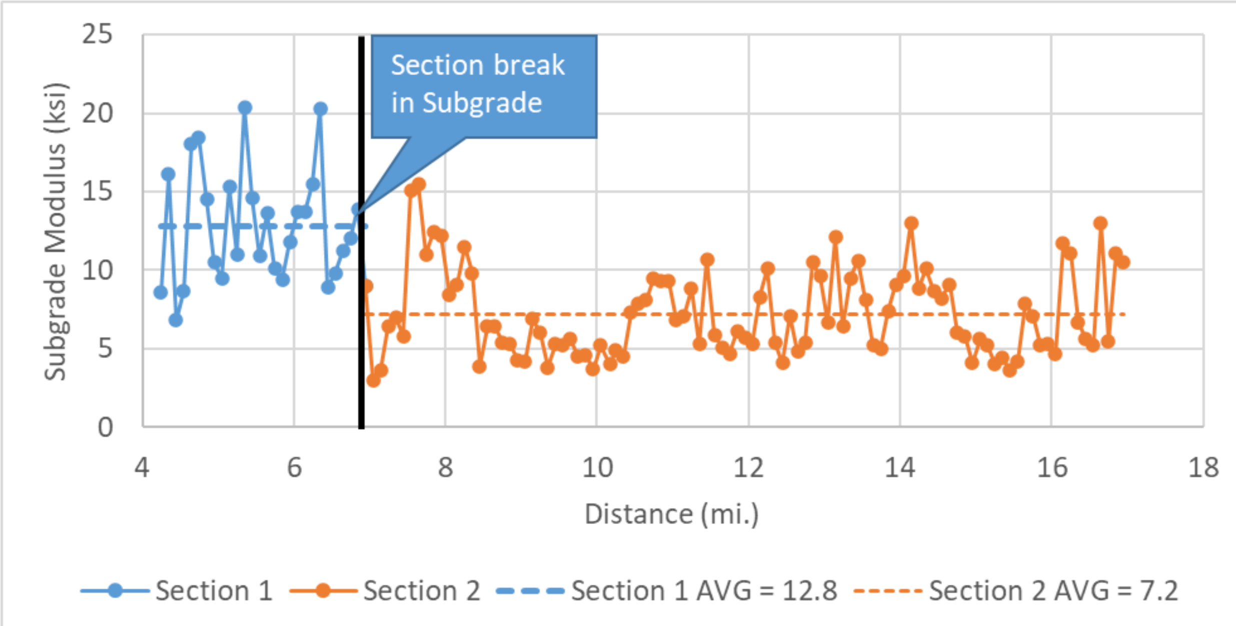


Figure 4. FWD analysis for project segmentation and determining subgrade quality.

Ground Penetration Radar Testing

GPR uses electromagnetic pulses to scan into the pavement nondestructively and, with air-coupled systems, can survey the pavement at highway speed with no need for traffic control. When scoping projects for potential subgrade stabilization, focus on using the GPR to evaluate (a) if any clear section breaks in the existing pavement structure exist and (b) if the GPR provides any indication of a wet or saturated subgrade. Figure 5 illustrates the results from a project where the GPR clearly shows a section break of different pavement structures. The existing typical section should be validated by coring and sampling with an auger within each of the sections to confirm the interpretation of the GPR data. Once validated, use the actual existing typical sections in further analysis and design of the project. Using GPR to detect potentially wet subgrade relies on the wetter subgrade material reflecting more energy back to the GPR antenna, which shows up in the GPR data as a higher amplitude/higher intensity subsurface signal.

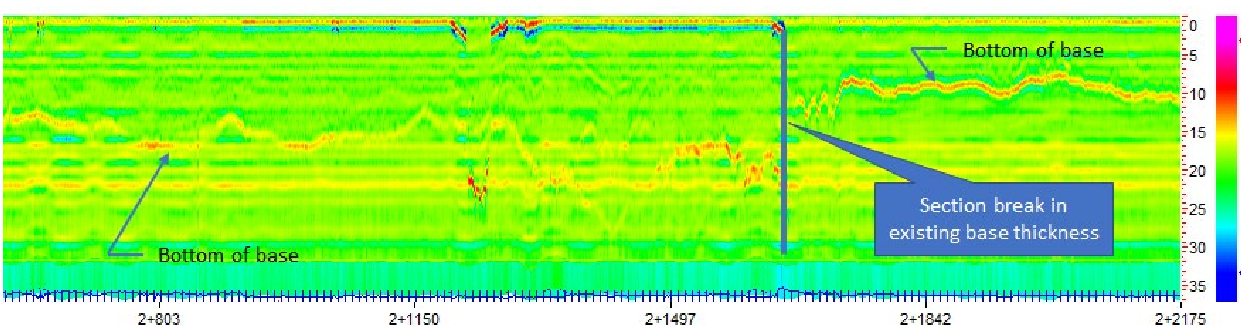


Figure 5. GPR showing section break, from thick to thin existing base, on a rehabilitation project candidate.

Dynamic Cone Penetrometer Testing

The DCP uses a hammer of specified weight dropped from a specified height to drive a pointed cone into the subgrade. The penetration rate serves to evaluate the subgrade bearing capacity and stiffness. Penetration rate or DCP index (mm/blow) can be correlated to the California Bearing Ratio (CBR) by using appropriate relationships developed by the United States Army Corps of Engineers.

Changes in the penetration rate indicate transitions to different materials, so the DCP can also help identify possible layer boundaries. DCP testing is often performed concurrently with soil sampling. Figure 6 (a) presents example DCP results where the penetration rate suggests three different soil horizons exist. Figure 6 (b) presents the estimated CBR with depth from the DCP penetration rate. Figure 6 (b) shows topsoil with CBR of 6%-20% up to 10 inches below the surface; from approximately 10 inches to 24 inches below the surface the soil becomes weak, and starting 24 inches below the surface, the soil becomes very weak.

Table 2 defines the threshold for low subgrade CBR vales.

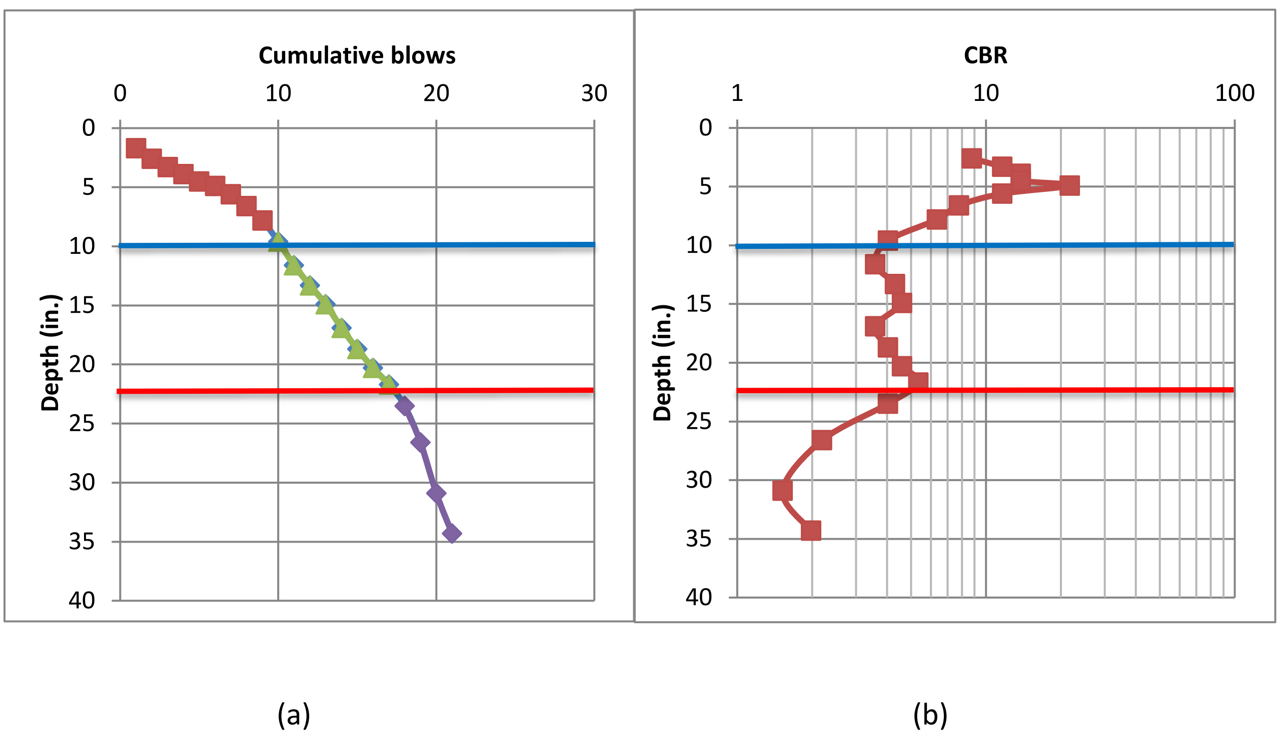


Figure 6. DCP results from soils in the project alignment: (a) graphed raw data with identified soil horizons based on penetration rate; (b) estimated CBR with depth.

Preliminary Soil Boring Information

Generally, limited pavement cores and soil borings are collected during project scoping. These pavement cores and soil borings provide information on existing pavement surface, base, and subbase thicknesses of existing pavements and underlying subgrade soil characteristics. Sampling spacing can be determined based on the USDA Soil Survey, FWD, and GPR information. Use the soil maps, FWD, GPR, and other available project records to identify locations to collect a sample representing each soil type anticipated along the project extents. If these data are not available, generally 1,000-ft spacing is recommended for 1-mi or longer projects or a minimum of five soil borings for projects < 1 mi long. Subgrade soil borings should include visual soil classification, moisture content, Liquid Limit (LL) and Plastic Limit (PL) limit tests, and DCP tests.

General guidance on sampling procedures, equipment, soil investigation, and characterization as well as various recommended in-situ soil tests can be found in the MDOT *Geotechnical Manual*.

Field Sampling and Testing Methods

Send the soil samples to a geotechnical laboratory for testing following the *Manual for the Michigan Test Methods (MTM)*. If the MTM is not available, the testing laboratory should follow appropriate ASTM or AASHTO test methods. The basic material tests for subgrade soils considered for chemical stabilization are shown in Table 1.

Table 1. Laboratory testing of subgrade soil considered for chemical stabilization.

Soil Property	Test Methods
Grain Size Analysis	AASHTO T 88 Standard Method of Test for Particle Size Analysis of Soils.
Soil Classification	ASTM D2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).
Moisture Content	MTM 407 Michigan Test Method for Natural Moisture Content Determination of Disturbed Soil Samples.
Atterberg Limits	AASHTO T 89 Standard Method of Test for Determining the Liquid Limit of Soils. AASHTO T 90 Standard Method of Test for Determining the Plastic Limit of Soils.
Loss on Ignition—Organic content	AASHTO T 267 Standard Method of Test for Determination of Organic Content in Soils by Loss on Ignition.
pH	ASTM G51 Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing.
Sulfate Content	AASHTO T290 Standard Method of Test for Determining Water-Soluble Sulfate Ion Content in Soil.

Preliminary Drainage Survey

A preliminary drainage survey is conducted during project scoping to evaluate problem areas of the roadway due to poor drainage conditions. Poor drainage conditions can cause premature pavement failure due to weak subgrade and base/subbase support. Chapter 7 of the MDOT *Project Scoping Manual* provides more details on the drainage survey. The following are the minimum information that should be included in the drainage survey during scoping: culvert condition, ditch information, storm sewer condition, channel condition, underdrain condition, spillway condition, county drains, and detention/retention basins. If the drainage cannot be corrected in certain areas of the roadway, subgrade stabilization of such areas with poor drainage should be avoided. Alternative methods, such as the use of thickened aggregate bases with geogrids, should be considered for such problem areas.

CRITERIA FOR SUBGRADE STABILIZATION

Based on the information collected during project scoping for new construction or reconstruction, subgrade stabilization should be considered when any of the conditions listed in Table 2 exist.

Table 2. Criteria for subgrade stabilization.

Condition	Criteria for Subgrade Stabilization
Subgrade	• If back calculated subgrade modulus from FWD < 5 ksi (If the AASHTO equation is used for calculating subgrade modulus, use the modified subgrade modulus), or • If the estimated CBR from DCP < 5%, or • If subgrade plasticity index > 15.
Pavement Life	• If the required pavement design life > 20 years. (only for concrete pavements)
Subgrade Modification for Working Platform	• If other existing site conditions suggest the subgrade is unsuitable for a working platform due to wet subgrade or the presence of marginal subgrade materials.

Use the subgrade criteria given in Table 2 and field investigation results detailed in the Field Investigation Guidelines section to develop limits for subgrade treatment. Some projects may justify subgrade stabilization throughout, while some projects may have more localized area(s) needing stabilization. In some projects due to shallow utilities or drainage structures, subgrade stabilization may be difficult to perform and these design elements should be checked thoughout the project selection process. Once treatment area(s) are identified, include the soil boring information from the treatment area that includes the detailed tests as shown in Table 1 to use as a basis of the bid.

Cost Comparison of Subgrade Treatment Options

Once the subgrade treatment area has been identified, a cost comparison of various subgrade treatment options should be carried out by the designer.

The following example shows a cost comparison of subgrade undercutting (remove and replace) versus subgrade stabilization for a one-lane mile road segment. Table 3, Table 4, and Table 5 present the subgrade treatment costs obtained from the awarded bid prices for the most recent projects in Michigan that used subgrade stabilization.

Table 3. Subgrade treatment costs for JN115799 I-69 from Ballenger Highway to Fenton Road (Construction Year 2018).

Item	Unit	Bid Price ($)
Lime stabilized subgrade	Syd	6.63
Lime	Ton	170.76
Estimated total cost of lime stabilized subgrade based on 5% application rate (12-inch subgrade stabilization)	Syd	11.24

Table 4. Subgrade treatment costs for JN117992 US-131 from 10 Mile Road to 17 Mile Road (Construction Year 2018).

Item	Unit	Bid Price ($)
Chemically stabilized subgrade	Syd	6.30
Lime	Ton	190.00
Cement	Ton	165.00
Estimated total cost of lime stabilized subgrade based on 5% application rate (12-inch subgrade stabilization)	Syd	11.43
Estimated total cost of cement stabilized subgrade based on 5% application rate (12-inch subgrade stabilization)	Syd	10.76

Table 5. Subgrade treatment costs for JN132102 US-24 from Grand River Avenue to 8 Mile Road (Construction Year 2023).

Item	Unit	Bid Price ($)
Chemically stabilized subgrade	Syd	6.30
Lime	Ton	213.00
Cement	Ton	125.00
Estimated total cost of lime stabilized subgrade based on 5% application rate (12-inch subgrade stabilization)	Syd	12.05

Estimated total cost of cement stabilized subgrade based on 5% application rate (12-inch subgrade stabilization)	Syd	9.68
The modified cost of 1-ft Type IV undercutting	Syd	18.26
The modified cost of 2-ft Type IV undercutting	Syd	36.51

The cost of subgrade undercutting was obtained from the MDOT 2022 Average Unit Price Report. The state-wide average unit price for Subgrade Undercutting Type II was $30.65/cyd. This price was modified to cost per square-yard basis for comparison purposes with other subgrade treatment options. The modified cost for 1-ft undercutting was $10.22/Syd, and the cost for 2-ft undercutting was $20.43/Syd.

Generally, subgrade stabilization will be used as a global treatment (a significant area of the project will be treated with subgrade stabilization), but subgrade undercutting will be used to treat localized problem areas. The following cost comparison chart was developed using different percentages of undercutting areas. The percentage undercutting area can be developed during the scoping stage of the project using the guidelines in Table 2.

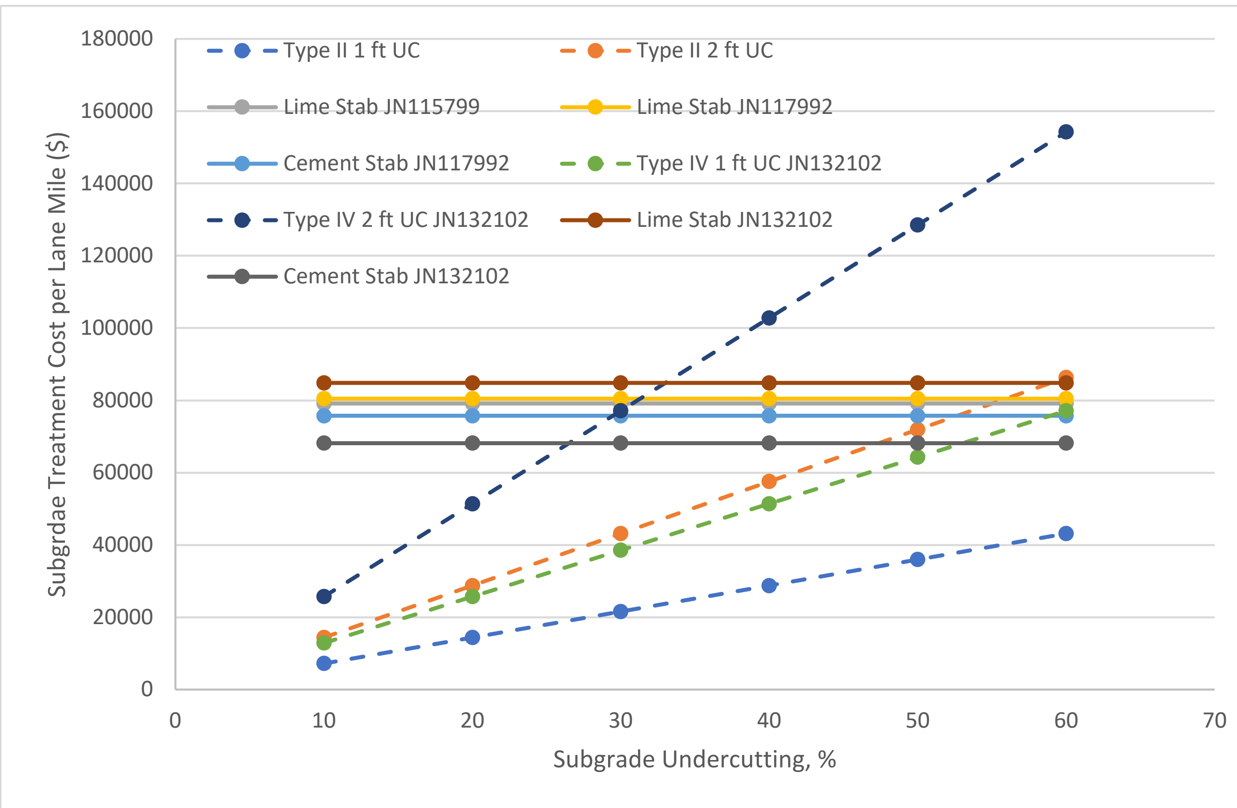


Figure 7. Subgrade treatment cost comparisons. (Illustrative purposes only. Project specific cost analysis should be performed.)

Figure 7 shows that, only considering the initial cost of construction, if 50–60 percent of the area needs 2-ft Type II undercutting, the use of subgrade stabilization for the whole project is economically justifiable. However, in the case of JN132102 (US-24 from Grand River Avenue to 8 Mile Road), the subgrade stabilization is cost-effective if 25% of the project area needs Type IV 2-ft undercutting. The above costs are only based on three subgrade stabilization projects. If subgrade stabilization becomes a standard practice in Michigan, the treatment cost may become less expensive. Furthermore, there are several other indirect cost savings or factors to be considered when selecting subgrade stabilization compared to subgrade undercutting; these include:

- Subgrade stabilization provides a uniform support for the pavement structure and enhances the future pavement performance.
- Subgrade stabilization may reduce the construction time by not requiring localized undercutting operations.
- Cost savings from potential pavement cross-section reductions approximately ½ inch of pavement.
- Dust pollution in urban areas; where applicable, dust control practices need to be considered.

DECISION TREE FOR SELECTION OF SUBGRADE STABILIZATION ADDITIVE BASED ON SOIL CHARACTERISTICS

While there are many factors to be considered during the selection of additive type for subgrade stabilization, Figure 8 can be used as initial screening criteria to select the additive type. When multiple additive types are listed, the best additive for the specific soil condition is always listed first. The other additives may be selected based on specific project requirements or constraints. Figure 8 was developed using Federal Highway Administration, National Cooperative Highway Research Program W144, and Texas Department of Transportation treatment guidelines. MDOT practice is to use contractor developed mix designs based on project specific subgrade conditions for subgrade stabilization projects.

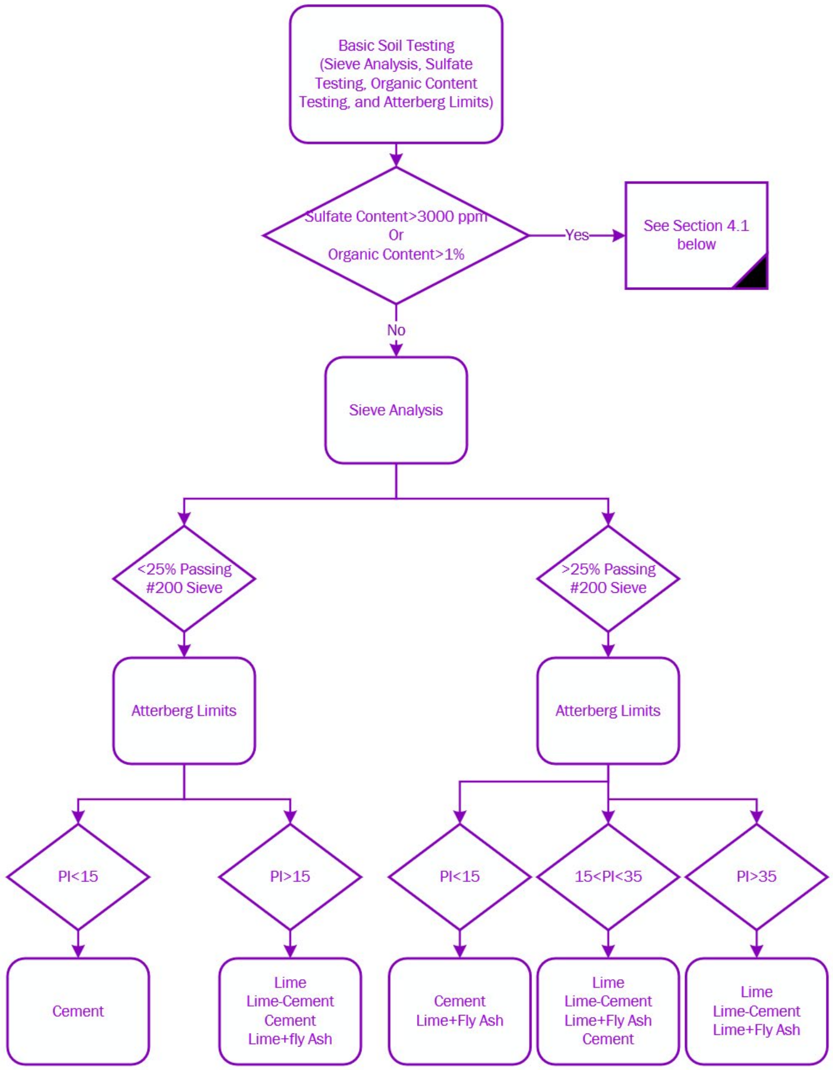


Figure 8. Decision tree for initial selection of subgrade stabilization material.

Guideline for Sulfate and Organic Bearing Soils

When the soils encounter more than 3,000 ppm of sulfate content or more than 1 percent of organic content, the following guidelines can be used for evaluating sites for subgrade stabilization.

Recommendations for Sulfate Bearing Soils

Sulfate bearing soils, when mixed with calcium-based stabilizers (e.g., lime, cement, or fly ash), can experience heaving problems due to the chemical reaction between sulfates and calcium modified soils. Previous research has shown that the heaving potential is significant when the sulfate content of soils exceeds 3,000 ppm. If the sulfate content is more than 3,000 ppm, do not treat with cement. Figure 9 provides recommendations for lime stabilization for soils with more than 3,000 ppm of sulfate.

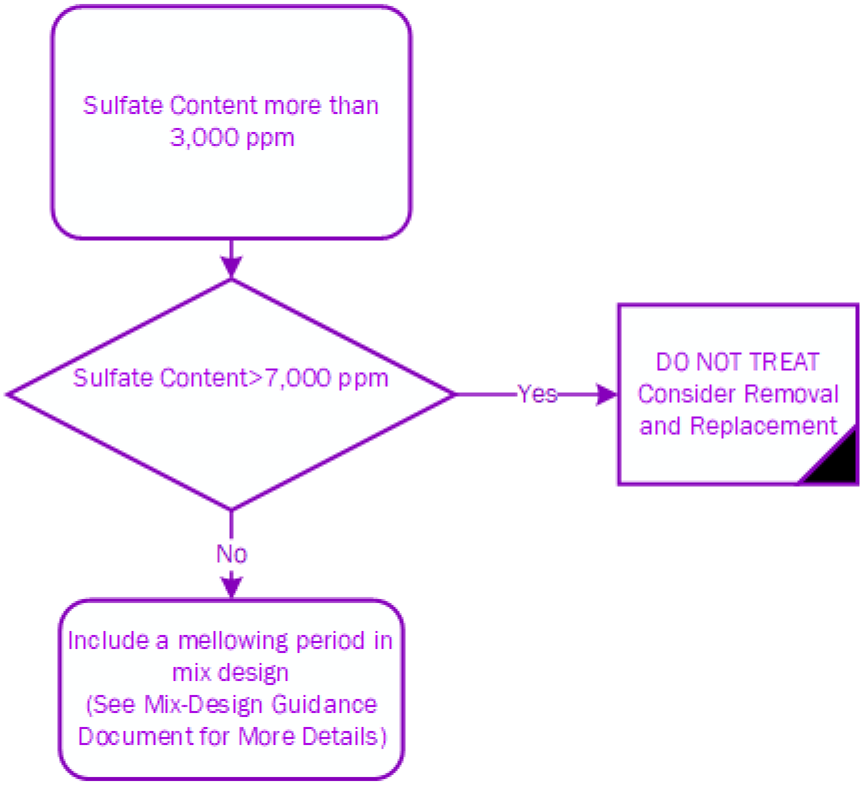


Figure 9. Determining potential lime treatment for sulfate bearing soils.

Recommendations for Organic Bearing Soils

It is difficult to stabilize soils with high organic matter. Organic matter prevents calcium-based stabilizers from reacting with soils. Figure 10 applies to soils with more than 1 percent organic matter.

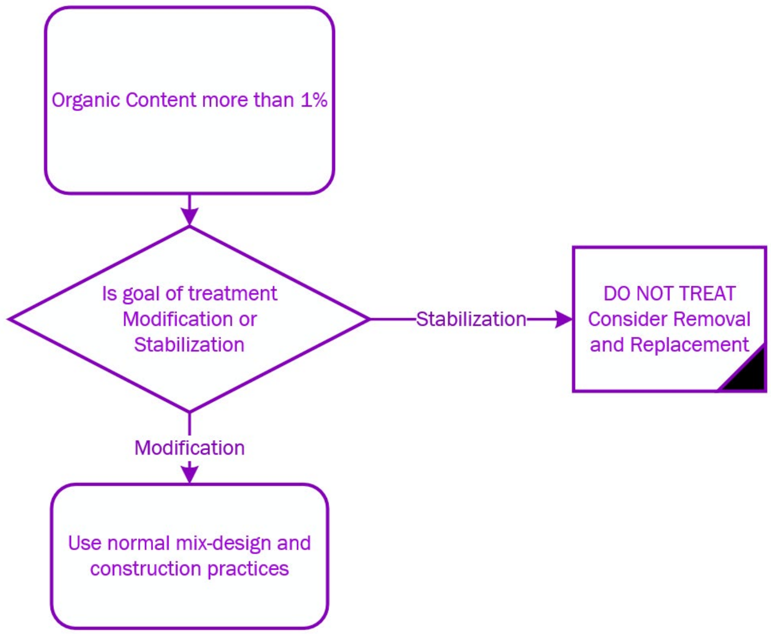


Figure 10. Determining treatment for organic bearing soils.

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TxDOT Treatment Guidelines for Soils and Base in Pavement Structures, Texas Department of Transportation, 2019

APPENDIX C: MIX DESIGN GUIDELINES FOR CHEMICALLY STABILIZED SOILS IN PAVEMENT STRUCTURES

Guidelines for Mix Design of Chemically Stabilized Soils in Pavement Structures

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INTRODUCTION

Pavement subgrade improvement measures must be designed to achieve target performance indicators during the construction phase and throughout the service life. Measures designed for the construction phase are defined as short-term modification techniques that provide sufficient strength to the subsurface layer that allows it to function as a construction platform for heavy equipment. This measure is denoted *subgrade modification*. The primary objective of modification is to limit the deflection and settlement under the construction wheel load.

Measures designed to act throughout the service life are defined as long-term stabilization techniques that provide adequate strength, uniformity, and durability of the subsurface layer that allows it to function as a foundation without causing excessive maintenance. The primary objective is to create a stronger and durable top layer in the in-situ subgrade. This measure is denoted as *subgrade stabilization*.

Site specific soil conditions greatly impact the selection of subgrade improvement measures. Site exploration aims to quantify the engineering properties of the in-situ soil as well as determine the presence of groundwater table, organics, and salts, in particular sulfates within the project area. The American Association of State Highway and Transportation Officials (AASHTO) and Unified Soil Classification System for coarse- and fine-grained materials are most commonly used to classify soils based on particle size and Atterberg limits. Coarse material is typically granular material that gains its strength from friction and interlocking of the grains. Fine-grained material can be either clay or silt.

The thickness of the soil improvement action is typically contained to the top 12 inches of the subgrade. However, the layer thickness can vary from about 8 inches to 18 inches based on the local conditions and the purpose of improvement. Therefore, it is recommended that soil sampling is performed to a depth of at least 2 feet below the proposed subgrade line (AASHTO R13).

Chemical Stabilization Mechanisms

Cement and chemical lime are the common chemical stabilizers used with subgrade soils. The terminologies associated with the stabilizing mechanisms are hydration and cementitious bonds, slaking, and pozzolanic behavior.

Hydration and Cementitious Bonds

Hydration of cement is a complex process that involves the reaction of finely crushed calcium-rich cement minerals and water. The hydration products, calcium silicate hydrates, are responsible for the cementitious bonds. The hydration process is controlled by the chemical composition of the cement, fineness, and, in particular, the temperature at which it reacts with water. The cement hydration is an exothermic process (i.e., releases heat). Stabilizing operations must be performed at above freezing temperatures.

Slaked Lime/Hydrated Lime

Limes in the form of calcium oxides, quicklimes, react with the free water in the soil and form calcium hydroxides while generating a significant amount of heat. Calcium hydroxides are called slaked lime or hydrated lime. The purity of the lime controls the rate of the slaking reaction, and the resulting process is quick, medium, and slow slaking. As the soil-lime mixture dries, the compaction can take place. Mellowing is often recommended prior to compaction. Mellowing is a time delay between mixing the lime with the soil and performing the final compaction. If the pH of the soil-lime mixture is at or above 12.5, pozzolanic reactions (with alumina and silicates) can occur with time to form cementitious bonds between the soil particles. A second process that takes place is the exchange of cations between the lime and clay soils. These actions will change the texture and plasticity of the soil. The development of cementitious bonds is a prerequisite to long-term strength and stabilization.

Pozzolanic Behavior

Pozzolan is a siliceous material. Pulverized pozzolan at room temperature will react with calcium hydroxide and water to form a cementitious hydration product, calcium silicate hydrates. Fly ash is a pozzolan with a grain size distribution similar to that of ordinary cement. Typically, Class C fly ash contains 3–6 percent calcium oxides, which is often adequate to initiate the pozzolanic reaction. Class F fly ash lacks calcium and requires supplemental materials (e.g., lime, lime kiln dust, cement, or cement kiln dust) to result in cementitious reaction products. These supplemental materials can be added up to about 20–30 percent of the fly ash by weight (NCHRP W144, 2009).

SOIL SAMPLING

Soil sampling for mix design may be performed, but is not necessarily always performed, in conjunction with upfront site exploration. Oftentimes, it is advantageous to have soil exploration results determined already according to the "Technical Guide—Selection of Pavement Projects for Chemical Stabilization of Subgrade Soils" prior to collecting soil samples for mix design. When collecting soil samples for mix design, the frequency of sampling typically is less than that used for upfront site investigation. However, for mix design sampling, the quantity of material collected at each location will be increased, and the depth of soil from which to sample will be constrained to that material most reasonably representative of the actual material anticipated for subgrade treatment. Thus, prior to soil sampling for mix design, an anticipated depth of pavement subgrade should also exist, which defines the anticipated location of the treated subgrade within the pavement structure and relative to the current grade line. Unless otherwise informed, when collecting soil samples for mix design, sample the materials to 2 feet below the final grade line.

Follow these general steps for locating and collecting soil samples for mix design:

1. Summarize and review the upfront site testing information obtained during scoping in accordance with "Technical Guide – Selection of Pavement Projects for Chemical

Stabilization of Subgrade Soils". Locate areas of different soil types, plasticity index, subgrade strength, suspected presence of organic matter or sulfates, or other subgrade site characteristics that may justify segmenting the project. Identify segment breaks based on this information.

2. Select at least one sample for every 20,000 square yards of subgrade area treated, or at least one for every major type of soil, or a minimum of 5 samples for each project, whichever is greater. Ideally, choose each of these locations near the vicinity of a prior-tested location from the upfront site selection process. For projects that do not have clear segmentations, select locations for sampling that represent the typical soil types.
3. At each location, collect a minimum of 200 pounds of subgrade soil representative of the actual anticipated depth of treatment. For example, if the anticipated subgrade depth calls for cutting 10 inches and then stabilizing 12 inches, collect the sample from 10 to 22 inches. Use methods of sampling in accordance with the Michigan Department of Transportation's (MDOT's) *Geotechnical Manual*, which may include but are not necessarily limited to auger boring or excavation with a backhoe or similar equipment.
   a. When sampling materials for use in mix design, if different materials are encountered with depth, collect a representative sample since these different materials will be uniformly mixed in the treatment process.
   b. Borrow sources, if anticipated, should be sampled separately.
4. Place the samples in suitable containers with unique sample identification, and return the soil samples to the materials lab for processing and further testing.

BASIC MATERIALS TESTS

The following material tests are recommended to be performed on untreated soil samples collected during the soil sampling process and treated soil samples with stabilizing materials. Table 1 lists the applicable ASTM, AASHTO, or Michigan Test Methods (MTM) standards. If the sulfate content is more than 3,000 ppm or the organic content is more than 1 percent of untreated soils, the contractor must inform the MDOT engineer immediately.

Table 1. Recommended Laboratory Testing of Untreated and Treated Subgrade Soil.

Soil Property	Test Methods for Untreated Soils	Test Method for Treated Soils
Grain Size Analysis	AASHTO T 88	*Not required*

Soil Property	Test Methods for Untreated Soils	Test Method for Treated Soils
Soil Classification	ASTM D2487	*Not required*
Moisture Content	MTM 407	*Not required*
Atterberg Limits	AASHTO T 89 and T 90	AASHTO T 89 and T 90
Loss on Ignition—Organic Content	AASHTO T267	*Not required*
pH	ASTM G51	ASTM D6276 (for lime-stabilized soil only) *Not required for cement-treated soils*
Sulfate	AASHTO T 290	AASHTO T 290
Optimum Moisture Content (OMC) and Maximum Dry Density (MDD)	*Not required*	Prepare samples using ASTM D3551 (for lime stabilized soil) and test using MTM 404 ASTM D 558 (for cement-stabilized soil)
Unconfined Compressive Strength (UCS)	MTM 405	AASHTO T208 (for lime-stabilized soils) ASTM D1633—Method B (for cement stabilized soil)

Soil Property	Test Methods for Untreated Soils	Test Method for Treated Soils
Expansion Testing	*Not required*	ASTM D4829

ADDITIVE SELECTION AND MIX DESIGN

Additive selection is based on the properties of the in-situ soils. Regardless of whether the goal of treatment is subgrade modification or subgrade stabilization, additive selection will require a similar process. Refer to the guidelines for additive selection in the Decision Tree for Selection of Subgrade Stabilization Additive Based on Soil Characteristics section of "Technical Guide—Selection of Pavement Projects for Chemical Stabilization of Subgrade Soils." The additive selection decision tree is shown in Figure 1 through Figure 3.

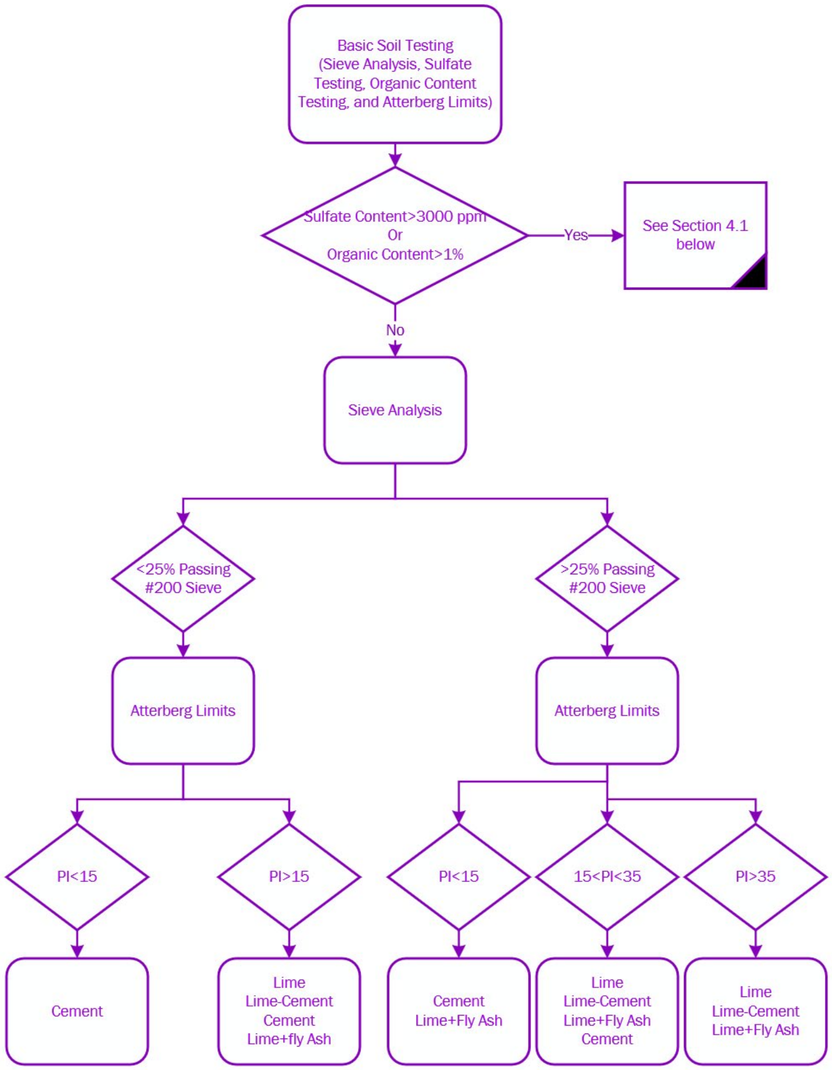

Figure 1. Decision tree for initial selection of subgrade stabilization material.

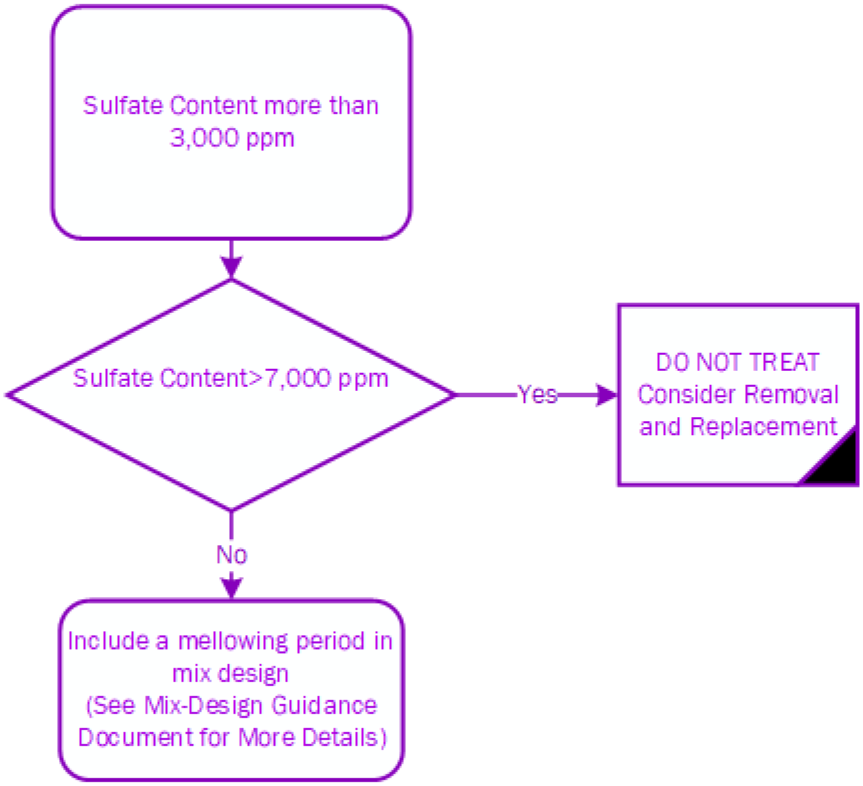

Figure 2. Determining potential lime treatment for sulfate bearing soils.

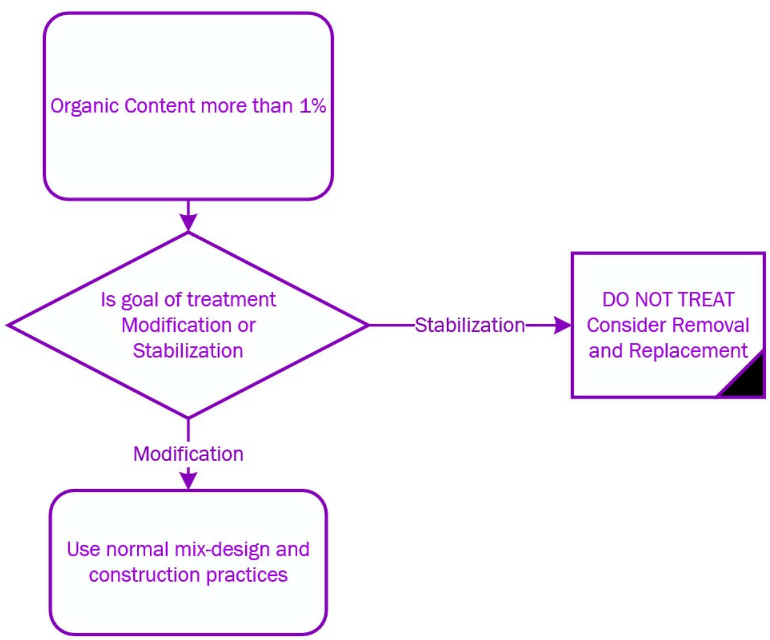

Figure 1. Determining treatment for organic bearing soils.

Regardless of the additive selection outcome, all subgrade soil treatments should undergo mix design. Generally, if the goal of treatment is stabilization, additional mix design tests and/or more stringent criteria will be required beyond the minimums for only modification. For modification, the mix design may use only indicator tests, reduced or no minimum compressive strength criteria, and historical experience with similar materials. For stabilization, mix design tests must include some type of minimum strength requirement.

Mix Design for Lime Stabilization

After initial project scoping, basic materials tests, and additive selection, perform mix design for lime treatment according to Table 2. The minimum recommended test for selecting a modification treatment rate is the pH test, while selecting a rate for stabilization requires a strength test. Regardless of the goal of treatment, if sulfates are present, additional effort may be required to identify whether and how the soil can be successfully treated.

Table 2. Required Mix Design Steps and Tests for Lime Treatment.

Step/Property	Test Method	Treatment Goal/Requirement	
		Modification	Stabilization
1. Determine the pH	ASTM D6276	Use minimum lime content to achieve a pH of 12.4.	Lime content must meet or exceed that required to achieve a pH of at least 12.4.

Step/Property	Test Method	Treatment Goal/Requirement	
		Modification	Stabilization
2. Determine sulfate content*	AASTHO T 290	• < 3,000 ppm. If sulfate content is > 3,000 but < 7,000 ppm, mellow the soil for at least 7 days after adding lime to reduce the sulfate content to < 3,000 ppm. • If sulfate content > 7,000 ppm, do not treat.	Same as modification.
3. Determine organic content*	AASHTO T 267	For information only**	If > 1%, do not treat. Consider remove and replace.
4. Determine OMC and MDD	ASTM D3551 and MTM 404	Determine the OMC and MDD. Use the lime percentage determined from ASTM D6276 for this determination. Prepare samples using ASTM D3551 and test using MTM 404. Mellowing time, if anticipated, should be included when determining the optimum moisture content and maximum dry density.	Same as modification.
5. Determine the risk of swell	ASTM D4829	Required only if sulfates on the untreated soil are > 3,000 ppm. Maximum Expansion Index (EI) < 50.	Same as modification.
6. Determine UCS	AASHTO T220	Not required	At least 50 psi greater than untreated soil and a minimum of 125 psi.

**These tests should have already been performed with the basic materials tests on the untreated soil.*
***Effectiveness of lime may be reduced if > 1% of organics are present.*

Mix Design for Cement Stabilization

As with the lime stabilization, after the initial project scoping, basic materials tests, and additive selection, perform mix design for cement treatment according to Table 3.

Table 3. Required Mix Design Steps and Tests for Cement Treatment.

Step/Property	Test Method	Treatment Goal/Requirement	
		Modification	**Stabilization**
1. Determine organic content*	ASTM D2974	Organics should be < 1% or cement effectiveness may be reduced.	If > 1%, do not treat. Consider remove and replace.
2. Determine sulfate content*	AASHTO T290	• < 3,000 ppm. • If sulfate content>3,000 ppm, do not treat with cement	Same as modification
3. Determine cement type and estimated dosage	Not applicable	Cement must comply with the latest specification for Portland cement and be available locally. Starting application rates can be 2% and 4% of the oven-dry weight of untreated soil.	Cement must comply with the latest specification for Portland cement and be available locally. Starting dosage rates can be 2%, 4%, and 6% of the oven-dry weight of untreated soil.
4. Determine Atterberg Limits of soils mixed with cement	AASHTO T 89 and T 90	Atterberg limits testing on treated soil with each cement contents. Testing must be completed within 1 hour of mixing.	Same as modification.

Step/Property	Test Method	Treatment Goal/Requirement	
		Modification	Stabilization
5. Determine OMC and MDD	ASTM D558	Determine the OMC and MDD of treated soils with each cement content.	Same as modification.
6. Determine UCS	ASTM D1633—Method B (for cement stabilized soil)	Not required.	A minimum of two specimens for each cement content should be prepared based on the optimum moisture content determined in Step 5. At least 50 psi greater than untreated soil and a minimum of 150 psi.

**These tests should have already been performed with the basic materials tests on the untreated soil.*

Lime-Fly Ash or Lime-Cement Dual Treatments

In some circumstances, dual treatments may be considered, such as lime-fly ash or lime-cement. Generally, these dual treatments use lime for its drying action and soil modification and fly ash or cement to promote the development of cementitious reaction products. Consider the goals of the dual treatment and evaluate if a single treatment product could achieve those goals before proceeding with a dual treatment mix design. Situations where a dual treatment may be desirable could include:

- Wet materials of relatively low to moderate plasticity index, where the drying action of lime is desirable prior to mixing in fly ash or cement.
- Elevated plasticity index soils where lime treatment alone did not yield a mix design meeting the strength requirement.

With dual treatments, the lime may or may not be added and mixed with a mellowing period prior to the addition of fly ash or cement depending on the materials and objectives of the dual treatment. Mix design methods should mimic the anticipated construction sequence, and the mix design report must describe in detail any mellowing time and any special sequence, curing methods, or timelines used.

For dual treatments with lime-fly ash, follow the steps for lime treatment in Table 2 and meet a minimum 150 psi UCS.

For dual treatments with lime-cement, follow the steps and meet the strength requirements of Table 3.

MIX DESIGN REPORT

The test report for treated soil mix design, at a minimum, should include:

- Unique sample identification.
- Designation of whether the design is for modification or stabilization.
- Target lime, cement, lime-fly ash, or lime-cement content.
- Atterberg limit test results.
- For lime stabilized soils, pH of the soil-lime mixture at target lime content.
- OMC and MDD of the treated soil mixture.
- Mellowing time, if applicable.
- Swell test results, if applicable.
- Unconfined compressive strength, if applicable.

MATERIALS

Use lime, cement, fly ash, and water that meet MDOT's *2020 Standard Specifications for Construction*.

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AASHTO, AASHTO R 13 Standard Practice for Conducting Geotechnical Subsurface Investigations, American Association of State Highway and Transportation Officials, Washington D.C., 2012

NCHRP, *Recommended Practice for Stabilization of Subgrade Soils and Base Materials,* NCHRP Web-Only Document 144, National Cooperative Highway Research Program, Transportation Research Board, Washington D.C., 2009

AASHTO T88 Standard Method of Test for Particle Size Analysis of Soils.

ASTM D2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).

MTM 407 Michigan Test Method for Natural Moisture Content Determination of Disturbed Soil Samples.

AASHTO T 89 Standard Method of Test for Determining the Liquid Limit of Soils.

AASHTO T 90 Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils.

AASHTO T 267 Standard Method of Test for Determination of Organic Content in Soils by Loss on Ignition.

ASTM G51 Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing.

ASTM D6276 Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization.

AASHTO T 290 Standard Method of Test for Determining Water-Soluble Sulfate Ion Content in Soil.

ASTM D3551 Standard Practice for Laboratory Preparation of Soil-Lime Mixtures Using Mechanical Mixer.

MTM 404 Michigan Test Method for The Moisture-Density Relations of Soils Using a 5.5 pound (2.5 kg) Rammer and a 12 inch (305 mm) Drop

ASTM D558 Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures.

MTM 405 Michigan Test Method for Unconfined Compressive Strength of Cohesive Soil.

AASHTO T 208 Standard Method of Test for Unconfined Compressive Strength of Cohesive Soil.

ASTM D1633 Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders.

ASTM D4829 Standard Test Method for Expansion Index of Soils.

ASTM D2974: Standard Test Methods for Determining the Water (Moisture) Content, Ash Content, and Organic Material of Peat and Other Organic Soils.

ASTM D3551: Standard Practice for Laboratory Preparation of Soil-Lime Mixtures Using Mechanical Mixture.

ASTM D4829: Standard Test Method for Expansion Index of Soils.

AASHTO T220: Standard Method of Test for Determination of the Strength of Soil-Lime Mixtures.

APPENDIX D: CONSTRUCTION GUIDELINES FOR CHEMICALLY STABILIZED SOILS IN PAVEMENT STRUCTURES

Guidelines for Construction of Chemically Stabilized Soils in Pavement Structures

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1. General Description

1.1 Background

Michigan's geological conditions include a wide variety of soils with varied consistencies and moisture conditions. A proper understanding of these soils is needed to use appropriate designs for roadway construction, rehabilitation, and widening projects. Depending on the properties of the existing subgrade, improvements such as mechanical stabilization or chemical stabilization may be required to construct pavement structures to withstand design traffic levels. Prior to construction, proper site selection and mix design must be performed. Guidelines for selecting projects for chemical stabilization are given in the *Technical Guide—Selection of Pavement Projects for Chemical Stabilization of Subgrade Soils (MDOT, 2023).* Further information on selecting the proper chemical stabilizer type and mix design method is provided in *Guidelines for Mix Design of Chemically Stabilized Soils in Pavement Structures (MDOT, 2023)*. This section provides a brief overview of the chemical stabilization process.

Chemically stabilizing subgrade soils provides benefits by increasing the strength of soils with low native strength. The rate of strength development and alteration of subgrade soil properties depends on several factors:

- Existing subgrade soil type, gradation, liquid limit, plastic limit, organic content, and sulfate content;
- Rate of stabilizer substance used;
- Type and properties of the stabilizer substance;
- Moisture content of the stabilized soil mixture during the stabilization process;
- Uniformity of mixing and mixing depth;
- Mellowing period, if any;
- Starting time of the compaction and compaction effort;
- Final density of the compacted layer;
- Ambient and soil temperatures during the stabilization process; and
- Curing method and duration.

1.1.1 Lime Stabilization

Mixing of lime with clayey soil results in three processes:

- Drying,
- Modification, and
- Stabilization.

When quicklime is used, the drying process starts immediately by hydrating lime with available water in the clay soils. The hydration process releases heat, which further evaporates the water in the clay. Quicklime is considered more hazardous than hydrated lime, and safety requirements for handling and working with this material should be strictly adhered to. Project staff should follow specific precautions in the Material Safety Data Sheet provided by the producer or supplier.

Modification refers to modification of the clay fraction of soils through ion exchange and flocculation of the clay minerals. After the initial mixing, the calcium ions (Ca^{++}) from hydrated lime displace water and other ions on the surface of clay particles. This process is called *flocculation and agglomeration* and makes the treated soil friable and granular as shown in Figure 1. This process takes place within 1–2 hours after mixing lime with the soil. After modification, friable soils are more easily broken apart and more workable in the field, thus enhancing constructability.

Figure 1. Lime-Treated Soils in Friable and Granular Condition (National Lime Association [NLA], 2004)

Stabilization refers to a long-term process where clay particles break down due to high pH values. This chemical reaction for stabilization continues so long as sufficient reactants are available. During stabilization, the silica and alumina in clay minerals react with lime and form calcium-silicate-hydrate (CSH) and calcium-aluminate-hydrate (CAH). Both CSH and CAH have cementitious properties and contribute to the strength of lime-stabilized soil layers. The cementation process takes longer and requires available clay minerals, moisture, and higher pH levels (generally above 12.0). Stabilization with lime typically uses a mellowing period of at least 24 hours before compaction to facilitate the chemical reaction between lime and clay minerals, and the stabilization reaction may continue over many months. Higher temperatures accelerate the chemical reaction, and lower temperatures (less than 40°F) retard the process. If the subgrade soils do not have sufficient silica and alumina for the chemical reaction, additional cementitious materials such as cement or fly ash need to be added for stabilization.

1.1.2 Cement Stabilization

Cement stabilization produces cementitious reaction products faster than lime stabilization. Mixing of cement with subgrade soils results in cementation. The cementation process alters the existing subgrade soils, resulting in a reduced plasticity index. This process does not require clay minerals to be present, and cement stabilization generally works for granular materials as well. For cement stabilization, the material mixed with cement needs to be compacted within 2 hours of final mixing.

Cement stabilization should be limited to an area that can be mixed and compacted within 1 working day due to the quicker process.

1.1.3 Subgrade Modification with Lime or Cement

Subgrade modification refers to the soil improvement during or shortly after mixing to improve engineering properties, including plasticity and moisture sensitivity, to facilitate or expedite construction operations. The contractor generally requests subgrade modification during the construction phase of the project.

1.2 Purpose of the Guidelines

This document provides information related to the construction of chemically stabilized subgrades. Construction guidelines are essential for subgrade stabilization projects to provide guidance for proper placement, mixing, compaction, and curing prior to placing the next layer of the pavement structure.

1.3 Scope of the Guidelines

Lime and cement are the primary stabilizer materials included in this guidance document. However, lime and fly ash or cement and fly ash combinations may be employed on some projects. The type of material (lime, cement, lime/fly ash, or lime/cement) is determined during the mix design process generally conducted by the contractor.

1.4 Definitions and Terms

The terms *stabilization* and *modification* are often used in this guidance document and are defined as follows.

Subgrade stabilization: long-term strengthening of subgrade soils to improve the uniformity, strength, and durability of the pavement structure. Subgrade stabilization is included in the construction documents, and performance improvement through stabilization is considered in the pavement design methodology.

Subgrade modification: short-term improvement of pavement subgrade soils to facilitate construction of the pavement structure. Generally, subgrade modification is not included in the construction documents, and contractors generally request this work item during the construction phase of the project due to poor subgrade conditions. These improvements generally include improved workability, limited deflection under heavy wheel loads to support construction traffic, and drying action. The pavement design methodology should not consider any subgrade performance improvements due to the modification.

Unless otherwise noted, subgrade modification is synonymous with stabilization where used in the subsequent text.

1.5 Guidelines Layout and Content

The layout of this guidance document has been structured for construction engineers and technicians to provide guidelines on materials, construction methods, construction inspection, and measurement methods. The guidelines are organized in the following chapters:

- Chapter 1: General Description;
- Chapter 2: Materials;

- Chapter 3: Equipment;
- Chapter 4: Pre-construction;
- Chapter 5: Construction of Stabilized Subgrade;
- Chapter 6: Inspection and Testing;
- Chapter 7: Measurement, Documentation, and Payment;
- Appendix A: Subgrade Stabilization Test Strip Checklist;
- Appendix B: Summary of Subgrade Stabilization Construction Process; and
- References.

2. Materials

The approved materials for subgrade stabilization include Portland cement, lime, fly ash (shown in Figure 2), and water for mixing and compaction. General requirements and testing of lime and cement are provided in Section 901 of the Michigan Department of Transportation (MDOT) *2020 Standard Specifications for Construction*.

Figure 2. Portland Cement, Lime, and Fly Ash

2.1 Lime

Lime in the form of quicklime, hydrated lime, or lime slurry can be used for subgrade stabilization. Quicklime (calcium oxide [CaO]) is manufactured by burning limestone (calcium carbonate [$CaCO_3$]). Hydrated lime ($Ca[OH]_2$) is created by mixing water with calcium oxide. Lime slurry is created by adding particles of quicklime to a water carrier or mixing dry hydrated lime with water. Lime slurry generally contains 35–45 percent solids, but other values may exist depending on the supplier. Slurry can provide some advantages including reduced dusting, complete hydration of the lime, and potentially faster and more complete reactions. However, slurry also increases the moisture content of the treated material, so slurry may not be preferable with materials that are already at (or above) optimum.

In soil stabilization, the hydrated lime reacts with the soil to form a stabilized soil layer. Sometimes, a limestone-based product used for agricultural purposes is also referred to as lime. However, agricultural lime is a finely ground limestone and does not possess any reactive ingredients for soil stabilization.

Most lime used in soil stabilization is called *high-calcium* lime and is derived from limestone. However, sometimes dolomite-based lime which contains 35–45 percent magnesium oxide or hydroxide is also available. Dolomite lime works satisfactorily for subgrade stabilization, but the magnesium fraction reacts at a slower rate than the calcium fraction. Therefore, intermixing different sources of lime should be avoided unless provided for in the mix design.

Lime (quicklime or hydrated lime) must be in accordance with ASTM C977. All quicklime must pass the 3/8-inch sieve.

2.2 Cement

The three types of Portland cements generally approved for use by MDOT are Type I–Type IL, Type II, and Type III Portland cements according to Section 901 of the MDOT *2020 Standard Specifications for Construction* and related contract documents. Any of these cement types are suitable for subgrade stabilization.

2.3 Fly Ash

Fly ash is a siliceous by-product of coal-burning power plants and is generally captured by electrostatic precipitators before the flue gases reach the chimney. Depending on the type of coal burned in the boiler, two types of fly ash are generally produced:

- Class C fly ash contains higher amounts of CaO and is generally both cementitious and pozzolanic in nature. This guide does not consider Class C fly ash for soil stabilization.
- Class F fly ash is not cementitious but pozzolanic, which contains less than 10 percent CaO. Class F fly ash may be used for soil stabilization together with lime or cement when the subgrade soils contain only a marginal amount of clay fraction.

For soil stabilization in Michigan, fly ash must be in accordance with ASTM C618 for Class F. The Class F fly ash must be selected from the list of approved manufacturers in the *Materials Source Guide (MDOT, 2024)*. The manufacturer must supply proper documentation by verifying the fly ash meets ASTM C618 requirements.

2.4 Water

Water must be in accordance with Subsection 911 of the MDOT *2020 Standard Specifications for Construction*.

3. Equipment

The key equipment to construct stabilized subgrade includes a spreader or distributor, rotary pulvimixer, compaction equipment, grading equipment, and water trucks. The contractor should demonstrate that all required equipment is available and in working order for construction before starting work.

3.1 Spreader or Distributor

Spreaders or distributors are non-pressurized mechanical vane-feed cyclone- or screw-type machines capable of providing a consistent, accurate, and uniform distribution for applying stabilizing agents and additives. The spreader or distributor must have a visible meter that displays the application rate and must be capable of minimizing dust during construction. Also, calibrated scales that capable of measuring the weight of stabilizing agent each day need to be available. Significant dusting during construction can cause reduced visibility for the public traveling through the work zone, can be a nuisance to nearby properties, and can result in a reduced rate of stabilizing agent mixed into the soil.

Figure 3 and Figure 4 show spreaders or distributors in dry form and wet form, respectively. Section 5.4 of this guide provides details about spreading stabilizers.

Figure 3. Quicklime/Cement Spreader or Distributor Spreading Portland Cement

Figure 4. Lime Slurry Spreader or Distributor (NLA, 2004)

3.2 Rotary Pulvimixer

A rotary pulvimixer must be used for all mixing. The pulvimixer must use a direct hydraulic drive and be capable of mixing at least a 12-inch layer depth in one pass. Pulvimixers are required because they can provide a more controllable mixing action—and thus a more homogeneous mixture—than other processes such as using rippers and a blade for mixing. Figure 5 shows a rotary pulvimixer. Section 5.5 of this guide provides details about mixing of stabilizers.

Figure 5. Rotary Pulvimixer Mixing in Lime Slurry

3.3 Compaction Equipment

Compaction equipment includes sheepsfoot or vibratory padfoot rollers, steel-wheeled smooth-drum rollers, pneumatic tired rollers, and tampers or plate vibrators. For stabilized subgrade, sheepsfoot rollers should generally be used for the initial compaction since they most effectively compact through the depth of the treated layer. Other rollers are used during the finishing process. Tampers and plate vibrators should only be used in locations not accessible to full-size compaction equipment. Figure 6 through Figure 9 show different types of compaction equipment. Section 5.7 of this guide provides details about the compaction of stabilized subgrades.

Figure 6. Sheepsfoot or Vibratory Padfoot Rollers

Figure 7. Steel-Wheeled Smooth-Drum Rollers

Figure 8. Pneumatic Tired Rollers

Figure 9. Plate Vibrator and Rammer/Tamper

3.4 Grading Equipment

A self-propelled motor grader (Figure 10) capable of shaping the material to the line, grade, and cross-section specified on the plans is required for construction. Section 5.8 of this guide provides details about final grading.

Figure 10. Self-Propelled Motor Grader

3.5 Water Trucks

Water trucks or other watering equipment is needed to control the moisture condition during the mixing of the stabilizer substance with the subgrade soils and during the curing stage of the stabilized subgrade. Watering equipment consists of tank trucks, pressure distributors, or other MDOT-engineer-approved equipment designed to apply controlled quantities of water uniformly over variable widths of surface. Water trucks may be connected to pulvimixers to inject compaction water directly through the mixing chamber, or water trucks may apply water topically by sprinkling to increase moisture content or to aid in working the material during finishing operations. Figure 11 shows typical watering equipment.

Figure 11. Typical Watering Equipment

4. Pre-construction

4.1 Contractor Qualification

Ensure the contractor has the necessary experience to perform subgrade stabilization work. The selected contractor should have a minimum of 5 years of experience in subgrade stabilization projects and experience with a minimum of five subgrade stabilization projects. The contractor needs to submit project experience information before or during the pre-production meeting.

4.2 Mix Design

It is essential that the contractor submit a mix design report prior to beginning construction of the stabilized subgrade. The contractor should use a geotechnical consultant experienced with stabilization design to perform the mix design. General guidelines on soil sampling, laboratory testing, selection of stabilizer type, and stabilizer percentage selection are provided in *Guidelines for Mix Design of Chemically Stabilized Soils (MDOT, 2024)*. If more than one predominant subgrade soil type is encountered, several mix designs may be needed for the construction project area.

The contractor should submit the mix design report to MDOT at least 10 days prior to the start of subgrade stabilization work to provide sufficient review time. The mix design report should include the following:

- Unique sample identification;
- Designation of whether the design is for modification or stabilization;
- Target lime, cement, lime–fly ash, or lime–cement content;
- Atterberg limit test results;
- For lime-stabilized soils, pH of the soil–lime mixture at the target lime content;
- Optimum moisture content and maximum dry density of the treated soil mixture with a multi-point compaction curve for compaction control;
- Mellowing time, if applicable;
- Swell test results, if applicable; and
- Unconfined compressive strength, if applicable.

The contractor-submitted mix design should be reviewed to make sure the mix design(s) reasonably align with the soil type(s) along the project. For example, if the project contains both low-plasticity and high-plasticity soils, and the mix design report uses the same rate of cement for the entire project, additional investigation should occur to confirm that the design is truly suitable for the different soil types. Generally, if soils have a plasticity index above 15, the mix design is expected to include lime. If the soil plasticity index is below 15, the mix design is expected to use cement. While there can be exceptions, a discrepancy should serve as a signal to initiate more dialogue with the contractor about the mix designs and the contractor’s planned construction process.

Using the mix design, the contractor and the testing technician are responsible for achieving the target stabilizer content, compacting to the designated density by using the optimum moisture content and maximum dry density, achieving the target strength requirement, and adhering to the proper mellowing time for lime stabilization during construction. Chapter 6 of this guide provides details about construction inspection.

5. Construction of Stabilized Subgrade

This section provides guidelines for how to properly construct a stabilized subgrade. Appendix B of this guide summarizes the construction procedure.

5.1 Seasonal and Weather Limitations

Freezing temperatures adversely affect the performance of stabilized subgrade, so freezing of stabilized subgrade should be avoided. Subgrade stabilization work should be performed when the air temperature is 40°F or above and rising. If the forecasted low temperature for the next 5 days is expected to fall below 40°F, it is not recommended to start subgrade stabilization work. It is also not recommended to apply cement, lime, lime–fly ash, or lime–cement when the temperature of the prepared subgrade surface is at or below freezing. The MDOT engineer may approve protective covers such as electric heating blankets to protect the stabilized subgrade from freezing.

Heavy rainfall (more than 0.25 in./hr) can also adversely affect subgrade stabilization during or shortly after the treatment. If heavy rainfall occurs during treatment, stabilizing chemicals may wash away from the construction area, and the contractor may have to reapply the proper percentage of stabilizer to the impacted area. The application, mixing, and compaction of soils after heavy rain may also be difficult due to wet conditions. Similarly, the moisture conditions of the stabilized material will be higher than the optimum for proper compaction. Therefore, subgrade stabilization work during heavy rainfall events should be avoided.

Light rain events could facilitate the construction of stabilized subgrade since light rain could limit dusting of dry lime or cement. The contractor and the testing technician should consider additional moisture from light rain events when measuring the moisture content for compaction.

5.2 Test Strip

Prior to full construction, the contractor should construct a test strip to demonstrate the contractor's ability to properly construct a stabilized subgrade with available equipment and the construction strategy. The test strip can be on an actual project area or an outside area adjacent to the project site. The selected test strip should be at least 300 ft in length and consist of one or more lanes. If not part of the project area for stabilization, the location should match the soil type of a work area to be stabilized. If more than one treatment type is specified in the plans, the contractor should perform a test strip for each stabilizer type.

The contractor must submit a plan of work for MDOT approval 10 working days prior to starting work on the test strip. The plan of work must include details of subgrade preparation, chemical application, initial mixing, final mixing, compaction, curing/protection processes, and testing. The MDOT engineer must review and approve the work plan prior to the commencement of work. The plan of work for the test strip needs to consider the following topics:

- The test strip should allow the contractor to determine optimal lot sizes (based on the application rate, mixing rate, mellowing time requirement, and compaction times), mixing times and rates, compaction moisture contents, compactor speeds, rolling patterns, and approximate number of passes required to achieve the required density and strength. The test strip should demonstrate proper subgrade preparation, application of chemical substances, initial mixing, final mixing, compaction, finishing, and curing. If the plan of work does not include required equipment or processes in accordance with MDOT specifications, the contractor should not be allowed to proceed with constructing the test strip until these concerns are addressed and resolved. Sections 5.3 through 5.9 in this guide provide additional details on best practices for the construction steps.

- The test strip should demonstrate proper inspection and testing. Prior to constructing the test strip, the contractor should designate its responsible party for testing and provide verification that the party has the proper training and equipment to perform the required testing. The contractor should not be allowed to proceed with constructing the test strip until the contractor has clearly identified the responsible party for its testing. Section 6 of this guide provides testing requirements.

During construction of the test strip, using the checklist provided in Appendix A to record observations during construction is recommended. A copy of this report should be provided with the Inspectors Daily Report (IDR) for MDOT records. The contractor must demonstrate achievement of proper application rate, moisture content, and mixing as well as attainment of the required level of pulverization, compaction, and required strength:

- **Application rate:** The application rate can be determined as follows. Use a metal, plastic, or canvas receptacle of a known area to capture the chemical substance placed by the spreader. Weigh the receptacle prior to use. Operate the spreader over the receptacle and spread the chemical substance at the anticipated rate. After spreading the substance, weigh the receptacle to determine the weight of the stabilization material. The stabilizer application rate can be determined using the following equation:

$$P = \frac{M \times 12}{L \times W \times T \times D}$$

where:

M = weight of the stabilizer in the receptacle

L = length of the receptacle in feet

W = width of the receptacle in feet

T = thickness of the stabilized layer in inches

D = density of the stabilized subgrade after compaction (lb/ft^3)

P = application rate of the stabilizer (as a decimal; 5 percent would be 0.05)

Example

Five percent cement must be mixed into a soil with a density of 125 lb/ft^3. The stabilized layer thickness is 12 in. The receptacle is 3 ft by 3 ft. The amount of cement deposited on the receptacle is 56.25 lb. The calculated application rate is:

$$P = \frac{56.25\ lb \times 12\ in./ft}{3\ ft \times 3\ ft \times 12\ in. \times 125\ lb/ft^3} = 0.05 = 5.0\%$$

calculate to the nearest 0.1% (or in decimal to the nearest 0.001)

Therefore, the correct application rate is used by the contractor.

Figure 12 illustrates checking the rate of application of chemical substances.

Figure 12. Checking the Chemical Substance Application Rate: (a) Place the Receptacle in the Middle of the Application Path, (b) Apply the Stabilizer, and (c) Weigh the Receptacle with Stabilizer to Determine the Application Rate (Jones et al., 2010)

- **Moisture content:** The moisture content can be determined as follows:
  - For lime stabilization projects, the in-situ moisture content is an important parameter to adjust moisture content during initial mixing. The in-situ moisture content can be determined using the nuclear density gauge or other MDOT-approved method prior to mixing with lime. The moisture content of the soil–lime mixture needs to be adjusted to 3–5 percent over the optimum moisture content provided in the mix design report. The plan of work should include how moisture content adjustments will be achieved. The best method is to inject compaction water through the mixing drum of a pulvimixer. If aeration is required, the best method is to pulverize the material and leave the material loose to remove water through evaporation. The contractor should demonstrate attainment of the proper moisture content during the test strip, and full production should not start until the test strip demonstrates attainment of the proper moisture content.
  - For cement stabilization projects, no water is required for initial mixing unless the initial and final mixing will be combined into one operation.

- **Mixing:** The initial mixing of lime or cement with the in-situ soils should be continued until a homogeneous, friable mixture is obtained, as shown in Figure 1.

- **Gradation:** The field gradation of the soil mixed with stabilizer needs to be checked as described in Section 5.5 of this guide. The gradation test is conducted to make sure that the stabilizer is completely mixed with in-situ soil and no large untreated clumps of clay exist within the mixing depth. For gradation testing, the general procedure given in Michigan Test Method MTM 109 can be used. The gradation test is conducted using three 500-g samples (a minimum of 1,500 g) obtained from random locations from the test strip, and the sieve analysis is conducted using only the 1-in. sieve and No. 4 sieve. Table 1 shows the gradation limits.

Table 1. Field Gradation Requirements.

Sieve Size	Minimum Percent Passing*
1 in.	100
No. 4	60

* Excludes rock particles.

- **Mellowing period:** Lime stabilization typically requires a mellowing period of at least 24 hours or the time specified in the mix design report. During the mellowing period, a chemical reaction with lime and clay minerals continues to change the clay particles to a more granular material structure. Since the moisture content is important during the mellowing period, prior to the start of the mellowing period, the contractor should lightly compact the stabilized layer with one or two roller passes to seal the surface of the subgrade and make sure the correct moisture content is maintained throughout the mellowing period. After the mellowing period, the stabilized materials need to be remixed prior to compaction. Section 5.6 of this guide describes this final mixing process.
- **Wet density:** The wet density of the stabilized material should be measured using a nuclear gauge, but the nuclear gauge moisture content measurements should not be used for the calculation of dry density. This is because the nuclear gauge detects the hydrogen in lime and cement as water. Instead, use a Speedy moisture gauge or other MDOT-approved method to measure the moisture content to calculate the dry density. Do not use the one-point density chart to calculate the maximum dry density and optimum moisture content. These values should come from a multi-point density curve from the mix design developed by the contractor.

- **Required strength:** After compaction, the test strip should verify the strength of the stabilized subgrade and the underlying in-situ subgrade using a dynamic cone penetrometer (DCP) as described in Section 6.1 of this guide. The DCP is also used to verify the stabilization depth.

5.3 Subgrade Preparation

During subgrade preparation, the contractor must establish the subgrade to conform to the line and grade shown on the plans prior to the application of chemical substances. The purpose of this preparation is to remove deleterious materials such as topsoil, roots, organic material, foreign debris, and rock fragments larger than 2½ inches because these items can impede the effectiveness of the stabilizing agent. The contractor must dispose of all deleterious material removed as part of subgrade preparation in accordance with Subsection 205.03.P of the MDOT *2020 Standard Specifications for Construction*.

5.4 Application of Chemical Substances

The contractor applies the contractor-designed quantity of chemical substance on a dry weight basis using a spreader or distributor. The contractor must verify the application rate once every 4,000 yards^2 or at least one time a day, and MDOT must verify the rate once a day. Section 5.2 of this guide presents how to perform this verification. Measured application rate results should be reported each working day. During application, lime or lime–fly ash should only be spread on an area where initial mixing can be completed within 4 hr. Due to its faster reaction rate, cement should only be spread on an area where initial and final mixing and compaction can be completed within 2 hr after application.

The spread chemical substance should appear uniform on the prepared subgrade. If the mix design uses multiple chemical substances, these substances may be spread individually. However, the method and timing of spreading and mixing these individual substances must match the methods used in the applicable mixture design. Uneven distribution of chemical substances should be avoided because it can result in localized zones of hot and lean treatment. Figure 13 shows examples of uneven distribution of chemical substances.

Figure 13. Uneven Distribution of Chemical Substances (Jones et al., 2010)

During application, there should be minimal dusting. Figure 14 shows dusting and scattering of cement. Dusting can be minimized by using powdered stabilizers in hydrated form, or for even more dust control, slurry may be used. Dusting can also be minimized when applying the stabilizer as a dry material by using a shroud extending down to the subgrade and/or a light sprinkling of water over the surface of the spread chemical substance. The contractor should not apply chemical substances when the MDOT engineer determines wind conditions result in dusting that creates potential hazards to traffic or becomes objectionable to property owners. In some sensitive locations, it may be necessary to use wet application methods to minimize dust.

Figure 14. Dusting and Scattering of Cement due to Wind (Jones et al., 2010)

5.5 Initial Mixing

The purpose of initial mixing is to provide initial pulverization of the subgrade soil material to allow the chemical substance to better disperse throughout and coat more surface areas of the soil.

5.5.1 Lime or Lime–Fly Ash

The contractor should begin mixing immediately after application using an approved rotary pulvimixer. The lime or lime–fly ash must be mixed into the subgrade to a depth sufficient to obtain a final compacted layer thickness as shown on the plans. Verify that the contractor brings the moisture content 3–5 percent above optimum and continues mixing until the lime or lime–fly ash is uniformly mixed to the required depth. A homogenous, friable mixture like that shown in Figure 1 indicates the attainment of uniform mixing. The contractor needs to complete the initial mixing within 4 hours of spreading the lime or lime–fly ash. Unless otherwise reported in the mix design, the contractor must mellow the mixture for at least 24 hours. Mellowing is essential for the proper reaction between lime or lime–fly ash with the clay minerals to break down the clay particles.

5.5.2 Cement

The contractor should begin mixing immediately after application using an approved rotary pulvimixer to thoroughly mix the cement into the subgrade to a depth sufficient to obtain the final compacted layer thickness shown on the plans. Do not add water during the initial mixing of cement with soil. Make sure the contractor continues mixing until the cement is uniformly mixed to the required depth. A homogeneous, friable mixture as shown in Figure 1 indicates the attainment of uniform mixing.

5.5.3 Depth, Uniformity, and Consistency of Initial Mixing

The mixing depth can be checked by digging holes (or using a probe) on both sides of the mixer as shown in Figure 15. Achieving a uniform blend can be checked by digging holes across the treated area and visually observing the consistency of mixed material as shown in Figure 16. The mixed materials should show uniform consistency, color, and moisture contents. If not, it is possible that the in-situ materials or moisture contents differed transversely across the roadway, the additive may not have been spread uniformly, or the pulvimixer may not be uniformly applying water across the spray bar in the mixing drum.

Figure 15. Checking Mixing Depth during Initial Mixing (Jones et al., 2010)

Figure 16. Visually Checking the Consistency of Mixed Materials (Jones et al., 2010)

In both lime- and cement-treated soils, the consistency and mixing depth can be checked by phenolphthalein solution. When applied to the soil, the indicator solution should immediately change color to a uniform deep red as shown in Figure 17.

Figure 17. Checking Stabilizer Mixing Consistency and Depth Using Phenolphthalein (Jones et al., 2010)

5.5.4 Field Gradation

Initial mixing should continue until the material meets the gradation in Table 1. The gradation test is conducted to make sure that the stabilizer is completely mixed with in-situ soil and no large untreated clumps of material exist within the mixing depth. After initial mixing, the MDOT engineer may sample the treated mixture at the required moisture content and determine compliance with Table 1.

For gradation testing, the general procedure given in Michigan Test Method MTM 109-01 can be used. Rock particles greater than 1 in. in size should be removed from the collected sample before sieving. Collect at least a 3.3 lb (a 1,500 g sample per each 4,000 yd^2 of stabilized area) or one sample per day for field gradation tests.

5.6 Final Mixing

The purpose of final mixing is to obtain a homogenous blend of chemical substance and soil at the proper moisture content prior to compaction. After final mixing, the material represents the final product in its uncompacted state.

5.6.1 Lime or Lime–Fly Ash

After the required mellowing time, the contractor should resume mixing until a homogeneous, friable material is achieved. The contractor must determine the moisture content of the mixture and add water as needed to bring the moisture content to 2–3 percentage points above optimum. The contractor can add water, when needed, through the mixing chamber of the pulvimixer unless another method has been approved.

The contractor must continue mixing to the required depth until the material meets the gradation requirements of Table 1. The soil mixture should be inspected as shown in Figure 16 for unhydrated lime or lime–fly ash particles before compaction. If suspected unhydrated lime or lime–fly ash particles exist, the MDOT engineer will determine whether additional mixing or mellowing is required prior to compaction. If mellowing time increases to a significantly longer duration than that used in the original mix design, it is possible a new moisture-density relationship may be needed.

After the final mixing, the MDOT engineer may sample the soil mixture at the required moisture and determine compliance with Table 1. When the plans include strength requirements, the MDOT engineer may sample the mixture to verify the strength.

5.6.2 Cement

Within 2 hours of initial mixing, the contractor must resume mixing, determine the moisture content of the mixture, and add water as needed to obtain the optimum moisture. The contractor may add water, when needed, through the mixing chamber of the pulvimixer unless another method has been approved. The moisture content should not exceed 3 percentage points above optimum; excessively wet material prior to compaction makes attaining the required dry density difficult during compaction.

After the final mixing, the MDOT engineer may sample the soil mixture at roadway moisture and determine compliance with Table 1. When the plans include strength requirements, the MDOT engineer may sample the mixture to verify the strength.

5.7 Compaction

Compaction should start immediately after the final mixing. Table 2 provides a guideline for the maximum time before starting the compaction after final mixing for various stabilizers. Make sure that the contractor follows these guidelines for the starting of compaction.

Table 2. Typical Maximum Compaction Start Times for Various Chemical Substances (Jones et al., 2010)

Stabilizer Type	Maximum Time Limit before Starting Compaction after Final Mixing (Hours)
Lime	6
Cement, lime–cement	0.5
lime–fly ash (Class F)	2

5.7.1 Lime or Lime–Fly Ash

Compaction should begin immediately after final mixing.

The contractor should maintain the moisture content during compaction at optimum ±2 percentage points. As quality control testing, the contractor needs to measure the moisture content of the material during compaction and report the results to the MDOT engineer the same working day unless otherwise directed. Not maintaining the moisture content within the required range could result in the material failing to achieve the required density. Additionally, materials excessively dry of optimum have less water present, which could impact the kinetics (the rate of the lime–soil reaction) of the lime–soil reaction.

Verify the contractor begins rolling at the outside edge and proceeds to the center, overlapping successive passes by at least one-half of the roller width. On superelevated curves, the contractor needs to begin rolling at the low side and progress toward the high side with successive passes. This rolling pattern will help maintain the superelevation. Make sure the contractor does not operate rollers in a manner that results in shoving or displacement of the treated mixture. Verify the contractor compacts treated subgrades to at least 95 percent of the maximum dry density unless otherwise shown on the plans. The MDOT engineer's representative will determine the roadway density in accordance with the MDOT *Density Inspection and Control Manual*. When an area fails to meet density requirements, make sure the contractor reworks the section to provide the required density. Materials that do not meet density could exhibit reduced strength and stiffness.

If the material is reworked more than 72 hours after compaction, the contractor needs to add 25 percent of the mix design lime or lime–fly ash rate when reworking, unless otherwise directed. Locations failing to meet the density requirement should be reworked at no additional project expense.

5.7.2 Cement or Lime–Cement

The compaction should begin immediately after the final mixing. Make sure that the contractor compacts the cement-treated mixture in one lift (if good compaction can be obtained throughout the stabilized layer), completing compaction within 2 hr after final mixing, unless otherwise approved. If a good compaction cannot be obtained with one lift, make sure that the contractor compacts the mixture in two equal lift thicknesses. Verify the contractor maintains the moisture content during compaction at optimum ±2 percentage points. Not maintaining the moisture content within the required range could result in the material failing to achieve the required density. Additionally, materials excessively dry of optimum have less water present, which could impact the kinetics of the cement–soil reaction. As quality control testing, verify the contractor measures the moisture content of the material during compaction and report the results to the MDOT engineer the same working dayunless otherwise directed.

Make sure that the contractor begins rolling at the outside edge and proceeds to the center, overlapping successive passes by at least one-half the roller width. On superelevated curves, the contractor needs to begin rolling at the low side and progress toward the high side with successive passes. This rolling pattern will help maintain the superelevation. At all times, the speed of the roller must not cause displacement of the mixture to occur. Verify that the stabilized layer compacts to at least 95 percent of the maximum dry density, unless otherwise shown on the plans. The MDOT engineer's representative will determine the roadway density in accordance with the MDOT *Density Inspection and Control Manual*. Materials that do not meet density requirements could exhibit reduced strength and stiffness.

When an area fails to meet density requirements, the contractor needs to remove and replace the material or rework the section by adding the mix design cement content, remixing, and recompacting to provide the required density, as directed or specified above. Locations failing to meet density requirements—requiring removal and replacement, or rework—should be corrected at no additional project expense.

Figure 18 shows the initial compaction of treated soil mixtures using padfoot rollers.

Figure 18. Use of Padfoot Rollers for Initial Compaction (Jones et al., 2010)

5.7.3 Miscellaneous Areas

The compaction of miscellaneous areas not accessible to rollers, such as temporary detours, driveways, mailbox turnouts, crossovers, gores, and other similar areas, should be performed using mechanical tampers or other approved equipment. Shaping and finishing these areas should be done by hand or other approved methods.

5.8 Finishing

Immediately after compaction, verify that the contractor shapes, fine-grades, and compacts the surface of the treated material to conform with the typical sections shown on the plans. Loosened material should be removed and disposed of at an approved location. Verify the contractor rolls the finished surface immediately, adding water by sprinkling as needed during rolling. The contractor needs to use pneumatic and smooth-drum steel wheel rollers during finishing. Typically, pneumatic and smooth-drum steel wheel rollers follow the blade during finishing operations, as shown in Figure 19.

Figure 19. Finishing with a Blade Followed by Pneumatic and Smooth-Drum Steel Wheel Rollers

5.9 Curing and Protection

Immediately after the stabilized subgrade has been compacted and finished, verify that the contractor protects the surface from rapid drying for 5 days by periodically sprinkling with water or by placing a curing coat of asphalt emulsion. This practice helps preserve moisture in the treated subgrade layer to promote the continuation of reaction products between the treatment and the soil. This practice can help minimize surface desiccation cracking.

When curing by sprinkling, the contractor needs to keep the subgrade moist for the full 5-day curing period unless covered by subsequent layers. If a curing coat is used, verify the contractor applies asphalt emulsion (prime coat emulsion) at a rate of 1 gal per 30 ft^2 as shown in Figure 20. Other suitable methods of curing the compacted stabilized subgrade may be used as approved by the MDOT engineer.

Figure 20. Prime Coat Emulsion for Curing (NLA, 2004)

After the curing period has elapsed, completed areas may be opened to construction traffic to commence the placement of subsequent pavement section layers. The contractor must protect finished portions of stabilized subgrade from marring and damage. The contractor is responsible for correcting and restabilizing damaged areas as determined by the MDOT engineer at no cost to the contract.

MDOT allows completed portions of stabilized subgrade to be opened immediately to light construction traffic at the contractor's own risk and option, provided the curing is not impaired. Placement of subsequent pavement layers may begin the day following the completion of stabilization only if the completed stabilized area has strengthened sufficiently. The strength of completed stabilized areas can be evaluated using proof rolling or DCP testing. The proof rolling can be performed using a loaded tandem axle truck (with a minimum 24 tons of gross vehicle weight) driving at walking speed. After one pass of the proof rolling truck, the observations of the subgrade should not show any pumping, cracking, or more than 0.5 in. of deflection under the wheel. Figure 21 shows a location where proof rolling clearly indicated inadequate stability. In the case of Figure 21, the location was well above optimum moisture and low dry density. Section 6.1 of this guide provides details about DCP testing.

Figure 21. Location of Inadequate Stability Determined by Proof Rolling

The contractor should not allow the treated subgrade to freeze during the curing period prior to placing subsequent layers. If the treated subgrade is not covered with base or pavement and is subjected to freezing, make sure the contractor adds an additional stabilizer and recompacts the treated subgrade before placing any base or pavement. The MDOT engineer, in consultation with the contractor's mix design consultant, will determine by laboratory or field strength tests the additional quantity of stabilizer to add, if any, and the extent of recompaction.

6. Inspection and Testing

Field quality control consists of contractor quality control and MDOT quality assurance tests. Table 3 and Table 4 present the type of testing and frequency of each type of field quality control.

Table 3. Contractor Quality Control Test Requirements

Test Name	Rate
Depth check	3 tests per 4,000 yd^2 or at least once per day
Calibrate chemical substance application rate	1 test per 4,000 yd^2 or at least once per day
Moisture content	1 test per 4,000 yd^2 or at least once per day

Table 4. MDOT Quality Assurance Test Rates

Test Name	Rate
Measure chemical substance application rate	Once per day
Depth and strength test (use the DCP to verify the treatment depth and the strength of the stabilized layer, or check the stabilized depth by phenolphthalein solution)	3 per every 4,000 yd^2 or at least once per day
Compaction (field nuclear density test)	1 per every 4,000 yd^2 or at least once per day
Moisture content	1 per every 4,000 yd^2 or at least once per day

6.1 Chemical Substance Application Rate

The chemical substance application rate should be measured as described in Section 5.2 of this guide.

6.2 Stabilized Thickness and Strength Test

The MDOT engineer's representative will use a DCP to verify that the minimum thickness shown on the plans has been uniformly stabilized and compacted. The stabilized depth can also be checked by phenolphthalein solution. The stabilized thickness and field stabilized subgrade strength must be evaluated in accordance with ASTM D6951. A maximum average DCP rate of 14 mm/blow in the stabilized zone is required for acceptance. Table 5 provides general guidelines for acceptance based on the thickness of the stabilized layer.

Table 5. Stabilized Layer Strength Acceptance Criteria Based on DCP Tests

Stabilized Layer Thickness (Inches)	Minimum Number of DCP Blows in the Stabilized Zone (after 1 Seating Drop)
8	15
12	22
18	33

The DCP test should start on the top of the stabilized subgrade. Use one seating drop to properly seat the DCP tip before recording cumulative penetration values. Figure 22 shows a typical DCP field operation.

Figure 22. DCP in Operation

The contractor must correct areas where the average DCP rate is more than 14 mm/blow by scarifying, adding additional chemical, remixing, and recompacting as directed by the MDOT engineer. All corrections must be completed with no additional cost to the contract.When the average DCP rate is more than 14 mm/blow, the MDOT engineer will verify the chemical application rate to determine whether the contractor is following the specification and mix design appropriately.

The DCP can also be used to measure the treatment depth. If the DCP will be used to measure the depth of the treated layer, the DCP should test to at least 12 in. below the bottom of the treated subgrade. Other methods for depth check can include digging holes (or using probes) as shown in Section 5.5 of this guide. When the measured thickness of the stabilized subgrade is more than ½ in. deficient, the contractor needs to correct these areas by scarifying, adding additional chemical, remixing, and recompacting as directed by the engineer. Where the measured thickness of the stabilized subgrade layer is more than ½ in. thicker than required, the stabilized subgrade will be considered conforming to the specified thickness, provided the elevation of the finished subgrade is within the tolerance specified in Section 205 of the MDOT *2020 Standard Specifications for Construction*.

6.3 Field Density Test

Perform density tests at the minimum frequencies listed in Table 4. For moisture content, do not use the nuclear density gauge because it tends to report inaccurate moisture content values when subgrade soils are stabilized with lime, lime–fly ash, or cement. Instead, use the Speedy moisture gauge or other approved methods to measure the moisture content. Use a multi-point density curve from the mix design developed by the contractor to obtain the maximum dry density and optimum moisture content. Do not use the one-point density curve to obtain the maximum dry density.

7. Measurement, Documentation, and Payment

The completed work, as described, is measured and paid for at the contract unit price using the pay items in Table 6.

Table 6. Pay Items

Pay Item	Pay Unit
Chemically stabilized subgrade	Square yard
Lime	Ton
Fly ash	Ton
Cement, special	Ton

7.1 Chemically Stabilized Subgrade

Chemically stabilized subgrade, as completed to the thickness and cross sections shown on the plans, is measured in square yards of horizontal surface area based on in-place quantity. All calculations of areas measured for payment must be based on measurements made to the nearest 0.1 yard with the area calculated to the nearest square yard. The length is measured along the surface of the completed roadbed parallel to the centerline. The width is the top surface width of the completed roadbed specified on the plans, measured perpendicular to the center line of the roadbed at 100-ft intervals. Additional areas required by the contract are measured by length and width along the surface area stabilized.

Chemically stabilizing a subgrade includes sampling; designing the cement, lime, lime–cement, or lime–fly ash combination soil mix; scarifying; pulverizing; mixing; shaping; watering; curing; applying asphalt emulsion; compacting; maintaining and applying cement, lime, and fly ash; testing including all labor; and providing equipment necessary to complete the work as described.

7.2 Cement, Lime, and Fly Ash

Cement, lime, and fly ash incorporated into the work are measured in tons. Payment includes furnishing, transporting, storing, handling, and spreading, including all labor, equipment, and materials necessary to complete the work as described. Certified delivery tickets must be furnished to the MDOT engineer for cement, lime, and fly ash incorporated into the stabilized subgrade for payment.

Appendix A: Subgrade Stabilization Test Strip Checklist

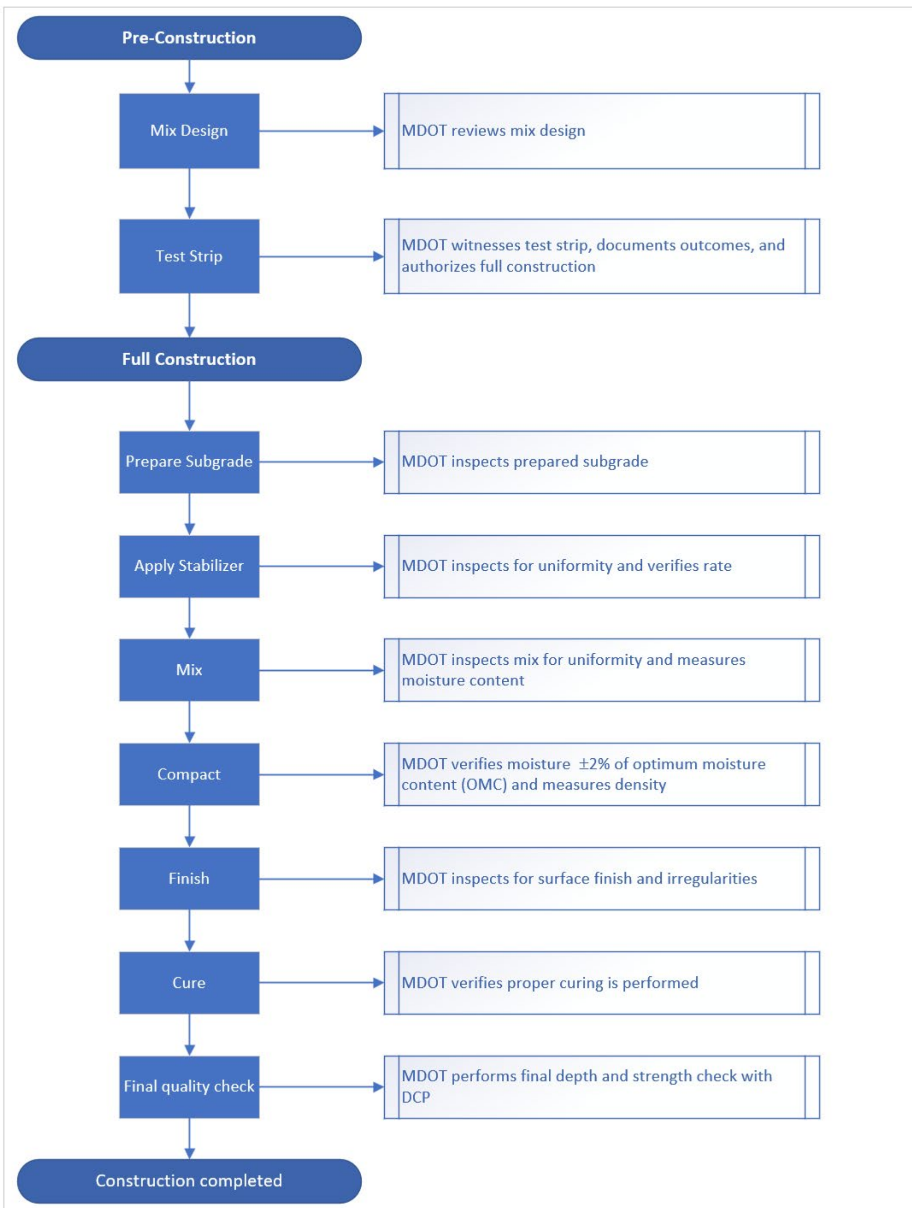
Project Number and Description:			
Region:	**TSC:**	**County:**	**Control Section:**
Check Item	**Yes**	**No**	**Action Items**
Equipment appropriate and calibrated	Y	N	
Site preparation satisfactory	Y	N	
In-situ moisture content measured	Y	N	
In-situ moisture content			
Optimum moisture content from mix design			
Water application rate adjusted for in situ	Y	N	
Ambient and surface temperature measured	Y	N	
Ambient temperature (degree, F)			
Surface temperature (degree, F)			
Stabilizer spread rate satisfactory	Y	N	
Spread rate			
Stabilizer spread uniformly	Y	N	
Lot size appropriate	Y	N	
Mix depth and uniformity satisfactory	Y	N	
Mix start time		Mix end time	
Mix depth			
Mellowing period satisfactory	Y	N	
Mellowing period			
Rolling pattern appropriate	Y	N	
Compaction speed and time satisfactory	Y	N	
Compaction start time		Compaction end time	
Number of roller passes			
Satisfactory compaction achieved	Y	N	
Measured density:		Avg. DCP penetration rate of stabilized layer	

Project Number and Description:			
Region:	**TSC:**	**County:**	**Control Section:**
Check Item	**Yes**	**No**	**Action Items**
Target density:		Avg. DCP penetration rate of in-situ soil below stabilized layer	
Moisture content:		Avg stabilized depth from DCP	
Final grading satisfactory	Y	N	
Quality control process satisfactory	Y	N	
Curing process satisfactory	Y	N	
Specification adhered to	Y	N	

Appendix B: Summary of Subgrade Stabilization Construction Process

Step	Contractor Role	MDOT Role
PRE-CONSTRUCTION ACTIVITIES		
Mix design	Provide mix design(s) for project material(s) at least 10 days prior to work.	Review mix design(s) for reasonableness with anticipated project material(s).
Test strip	Develop and submit plan of work to include subgrade prep, application of stabilizer, mixing, compaction, curing, finishing, and testing. Construct test strip.	Review plan of work. Record outcomes during construction of test strip. Pending outcome of test strip, authorize full construction.
FULL CONSTRUCTION ACTIVITIES		
Subgrade preparation	Remove deleterious materials.	Inspect prepared subgrade.
Application of stabilizer	Apply mix design rate using a spreader. Verify the applied rate once per 4,000 yards^2 or at least once per day.	Inspect spread stabilizer for uniformity. Verify the applied rate once per 4,000 yards^2 or at least once per working day.
Mixing	Perform initial mixing, mellowing (if called for in the mix design), and final mixing to the depth required to obtain a homogenous, friable material at the required moisture content. Measure depth 3 times per 4,000 yards^2 or at least once per day. Measure moisture once per 4,000 yards^2 or at least once per day.	Inspect mixing process for uniformity and thoroughness of mixing. Inspect for unhydrated stabilizing agent in the loose mix. Confirm mellowing time is followed per the mix design. Measure depth 3 times per 4,000 yards^2 or at least once per day. Measure moisture content once per 4,000 yards^2 or at least once per day.
Compaction	Maintain required moisture during compaction and compact the full depth of the treated layer to at least 95% density. Test density once per 4,000 yards^2 or at least once per day.	Verify material maintains moisture within optimum ±2 percentage points and attains at least 95% density. Test density once per 4,000 yards^2 or at least once per day.

Step	Contractor Role	MDOT Role
Finishing	Fine-grade and compact the surface of the treated material, removing and disposing of loosened material at an approved location.	Inspect the material for surface finish and reaction under equipment loads. Inspect for weak, excessively wet, dry, or unstable areas during the finishing operation.
Curing	Cure for 5 days by sprinkling or asphalt curing the membrane.	Verify proper curing protocol is performed.
Final depth and strength check	Not applicable.	Perform DCP 3 times per every 4,000 $yards^2$ or at least once per day.



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APPENDIX E: SPECIAL PROVISION FOR CHEMICALLY STABILIZED SUBGRADES

MICHIGAN
DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION
FOR
CHEMICALLY STABILIZED SUBGRADE

a. Description. This work consists of furnishing all labor, equipment, materials and testing necessary to construct a compacted uniform layer of chemically stabilized subgrade to a thickness provided in the plans and determining the minimum amount of cement, lime, lime-cement or lime-fly ash combination and water required for the soil.

Perform the work at the locations shown on the plans and in accordance with this special provision, the standard specifications and as directed by the Engineer.

Provide onsite staff with a minimum of 5 years' experience in subgrade stabilization and a minimum experience of 5 completed projects. Submit project experience information before or during the pre-production meeting.

For bidding purposes only, the minimum rate of cement application is six percent on a dry weight basis of the soil, the minimum rate of lime application is five percent on a dry weight basis of the soil. Fly ash may or may not be required as determined by the Contractor-Provided Mixture Design. For bidding purpose only, the estimated quantity of fly ash is 1,000 tons.

Selection of cement, lime, lime-cement or lime-fly ash mixture as the stabilizing agent shall be determined by the Contractor's mix design.

b. Materials.

1. Cement. Furnish Portland cement in accordance with section 901 of the Standard Specifications for Construction.

2. Lime. Furnish quicklime, hydrated lime or lime slurry in accordance with *ASTM C977* with the modification that all quicklime must pass the 3/8-inch size sieve. The lime will be accepted with Test Data Certification in accordance with the Materials Source Guide and must represent each lot of lime delivered to the project.

3. Fly ash. Furnish fly ash is in accordance with *ASTM C618 for Class F*. Bulk fly ash may be transported dry in bulk trucks and stored in tanks or may be transported in dampened condition (15 percent moisture, maximum). Only provide Class F fly ash from the list of Approved Manufacturers in the Materials Source Guide.

4. Water. Ensure water for mixing and curing is in accordance with section 911 of the Standard Specifications for Construction.

5. Soil. Soil used in this special provision is the existing in-place subgrade soil material. Ensure the soil is uniform in quality and gradation, is free of roots, sod, weeds, foreign debris

and stones larger than 2½ inches and approved by the Engineer.

6. Asphalt Emulsion. Furnish type SS-1h or CSS-1h asphalt emulsion in accordance with section 904 of the Standard Specifications for Construction.

c. Contractor-Provided Mixture Design. Develop and submit for approval a mix design specifying percent of cement, lime, lime-cement, or lime-fly ash combination in the soil to be stabilized. Develop and submit a sampling plan to the Engineer for review and approval prior to sampling the soil. Take at least one sample for every 20,000 square yards of subgrade area treated, or at least one for every major type of soil, or a minimum of 5 samples for each project, whichever is greater.

At each sample location, collect a minimum of 200 pounds of subgrade soil representative of the actual anticipated depth of treatment. Submit samples to an *AASHTO* or *ASTM* accredited geotechnical testing laboratory to determine the recommended percentage of stabilizer for each soil type taken. The accreditation must include all applicable *AASHTO* and *ASTM* test procedures referenced in this special provision.

The *AASHTO* or *ASTM* accredited geotechnical testing laboratory must perform the tests and services for the untreated soil listed in Table 1. The lab must perform the tests on the chemically treated soil in Table 2 for lime or lime-fly ash treatment. For treatment using cement or lime-cement the lab must perform the tests in Table 3. Prepare samples with the same stabilizing material(s) from the same material suppliers that will be used for the project. The contractor is responsible for selecting and determining the treatment type and rate to produce a mix design meeting requirements.

Table 1. Required geotechnical laboratory tests for untreated soils.

Soil Property	Test Methods	Specification Limits
Grain Size Analysis	*AASHTO T 88*	None
Soil Classification	*ASTM D2487*	None
Moisture Content	MTM 407	None
Atterberg Limits	*AASHTO T 89 and T 90*	None
Loss on Ignition – Organic content	*AASHTO T 267*	If the organic content > 1%, do not treat. Notify the Engineer immediately.
pH	*ASTM G51*	None
Sulfate	*AASHTO T 290*	• Sulfate content should be < 3,000 ppm. • If sulfate content is > 3,000 ppm, do not treat with cement • If sulfate content is > 3,000 but < 7,000 ppm, mellow the soil for at least 7 days for lime stabilization after adding lime

Soil Property	Test Methods	Specification Limits
		to reduce the sulfate content to < 3,000 ppm. • If sulfate content > 7,000 ppm, do not treat with lime notify the Engineer immediately.
Unconfined Compressive Strength (UCS)	*MTM 405*	None

Table 2. Required steps, test methods, and requirements to document mix design for lime and lime-fly ash stabilization.

Step/Property	Test Method	Specification Limits
1. pH	*ASTM D6276*	Lime content must meet or exceed that required to achieve a pH of at least 12.4.
2. Optimum moisture content and maximum dry density	*ASTM D3551* and *MTM 404*	Use the lime percentage determined from *ASTM D6276* for this determination. Mellowing time, if anticipated, shall be included when determining the optimum moisture and maximum dry density.
3. Expansion Index	*ASTM D4829*	Required only if sulfates on the untreated soil are > 3,000 ppm and <7,000 ppm. Maximum Expansion Index (EI)<50.
4. Unconfined compressive strength	*AASHTO T-220*	At least 50 psi greater than untreated soil and a minimum of 125 psi*

*Minimum 150 psi UCS for dual treatments with lime-fly ash.

Table 3. Required steps, test methods, and requirements to document mix design for cement and lime-cement stabilization.

Step/Property	Test Method	Specification Limits
1. Determine cement type and estimated	Not applicable	Use a minimum three dosage rates between 0% to 7% (i.e. 0%, 3%, 5%, and 7%) of the

Step/Property	Test Method	Specification Limits
dosage		oven-dry weight of untreated soil.
2. Atterberg Limits	*AASHTO T 89* and *T 90*	Determine Atterberg limits on treated soil with each cement content. Complete testing within 2 hours of mixing cement.
3. Optimum Moisture Content and Maximum Dry Density	*ASTM D558*	Determine the optimum moisture content and maximum dry density of treated soils with each cement content
4. Unconfined Compressive Strength	*ASTM D1633* – Method B	At least 50 psi greater than untreated soil and a minimum of 150 psi

Submit copies of test reports from the geotechnical lab with all data to the Engineer for review and approval at least 10 calendar days prior to starting the work.

Once the Engineer accepts the stabilizer percentages, the Contractor's qualified representative or geotechnical engineer must provide moisture density curves for the treated soil mix in accordance with *AASHTO T99* for each soil type. Allow treated soils to mellow per the mix design requirements when making the curves. Submit the moisture density results to the Engineer at least 10 calendar days before the work begins. The Engineer will use these curves and the *Density Testing and Inspection Manual* for compaction acceptance.

d. Equipment. Furnish approved equipment to conduct the work and maintain the equipment in satisfactory condition at all times. Other compaction equipment may be used in lieu of that specified where it can be demonstrated that the results are equivalent. Furnish protective equipment, apparel, and barriers to protect eyes, respiratory system, and skin of workers who may be exposed to cement, lime or fly ash.

1. Mechanical Spreader. Spreaders or distributors are non-pressurized mechanical vane-feed cyclone or screw-type machines capable of providing a consistent, accurate and uniform distribution for applying stabilizing agents and additives. The spreader or distributor must have a visible meter that displays the application rate and must be capable of minimizing dust during construction.

2. Rotary Pulvimixer. The equipment for pulverizing and mixing the existing pavement materials shall be a self-propelled machine capable of pulverizing in-place the existing pavement at a minimum width of 7.5 feet at the specified minimum depth. The cutting drum shall have the ability to operate at various speeds (RPM), independent of the machine's forward speed with an adjustable mechanism to control gradation. The machine shall be capable of pushing a tanker via an interlocking push bar and be capable of directly injecting additional water into the mixing drum. The machine shall be capable of regulating and monitoring the liquid application rate relative to depth of cut, width of inject, advance

speed, and material density. The cutting drum should be composed of a “chevron” style or “double hit” style tine pattern and be maintained in good condition at all times. Drum’s with random tine pattern will be allowed only if approved by the Engineer.

3. Calibrated Scales. Provide calibrated scales that capable of measuring the weight of stabilizing agent each day

4. Sheepsfoot or Vibratory Padfoot Roller. Self-propelled with a minimum weight of 15 tons or greater as needed for compaction.

5. Steel-Wheeled Smooth Roller. Self-propelled steel-wheeled rollers with a total weight of at least 10 tons and a minimum weight of 300 pounds per inch width of rear wheel. Ensure the wheels of the rollers are equipped with adjustable scrapers. The use of vibratory rollers is optional.

6. Pneumatic-Tired Roller. Ensure pneumatic-tired rollers are self-propelled and weigh when ballasted at least 8 tons but not more than 30 tons. Ensure the roller is equipped with a minimum of seven wheels situated on axles in such a way that the rear group of tires will not follow in the same tracks of the forward group of tires.

7. Motor Grader. Use a self-propelled motor grader capable of shaping the material to the line, grade, and cross section specified on the plans.

8. Watering Equipment. Watering equipment consists of tank trucks, pressure distributors, or other Engineer-approved equipment designed to apply controlled quantities of water uniformly over the stabilized area.

9. Tamper. Ensure tampers are an Engineer approved mechanical type, operated by either pneumatic pressure or internal combustion, and must have sufficient weight and striking power to produce the compaction required.

e. Construction.

1. General. Perform subgrade stabilization work when the air temperature is 40° F or above and rising. If the forecasted low temperature for the next 5 days is expected to fall below 40° F, do not start subgrade stabilization work. Do not apply cement, lime, lime-cement or lime-fly ash combination to frozen or frosted subgrade under any circumstances. Do not apply subgrade stabilization materials during heavy rainfall (more than 0.25 in/hr). Uniformly mix the Contractor-designed percentage of the stabilizing material through the entire stabilized depth and compact the subgrade to at least 95 percent of the maximum unit weight. Ensure adequate drainage is provided during the entire construction period to prevent water from collecting or standing on the area to be stabilized or on pulverized, mixed or partially mixed material. Do not apply cement, lime, lime-cement or lime-fly ash combination to standing or pooling water. Finished stabilized subgrade must conform to the line and grade as shown on the plans. Ensure adequate soil erosion and sedimentation control (SESC) measures are in place and maintained.

2. Chemical Stabilization Omission/Modification Locations. If during construction the Engineer determines that certain locations are inappropriate for chemical stabilization, the treatment may be omitted, substituted for another method, or the Engineer may request a

modified stabilization procedure.

3. Test Strip. At the start of this work, a 300-foot test strip comprising of either one or more lane widths (depending upon construction staging) will be selected and approved by the Engineer to initiate the subgrade stabilization. Submit a work plan for the test strip a minimum of 10 working days in advance of construction of the test strip. The plan of work must include details of subgrade preparation, chemical application, initial mixing, final mixing, compaction, curing/protection processes, and testing. Ensure the work for this test strip is in accordance with this special provision. After approval of the test strip by the Engineer, the Contractor may proceed with the production stabilization of the subgrade. At the Engineer's discretion, the test strip may be accepted as part of the total required chemically stabilized area. If not part of the plan area for stabilization, the test strip location will match the soil type of a plan area to be stabilized. When a material source is changed or different soil conditions are encountered, the Engineer may require a new test strip.

4. Subgrade Preparation. Prior to adding stabilizing materials, remove all deleterious materials such as topsoil, roots, organic material, foreign debris and rock fragments larger than 2½ inches. Grade the subgrade treatment area to conform to the line and grade shown on the plans prior to being processed for stabilization. Dispose of deleterious material removed as part of subgrade preparation in accordance with subsection 205.03.P of MDOT Standard Specification for Construction.

5. Chemical Application. Spread the Contractor-designed quantity of chemical on a dry weight basis uniformly on a scarified subgrade using a spreader or distributor. Place a canvas shroud on the distribution bar and extend the shroud down to the subgrade. Do not apply the chemical when the wind conditions are such that blowing material would become objectionable to the adjacent property owners or create potential hazards to traffic. To enhance dust control, the Contractor may use moisture conditioned fly ash. Lime and fly ash can be spread as individual components. While spreading the stabilizer, minimize dusting and impact to the traffic by periodic water sprinkling at no cost to the contract.

Conduct verification testing to show that the chemical is being applied at the required application rate. Provide the results to the Engineer at the completion of the test. The verification testing shall consist of the following.

a. Incorporate a receptacle made of metal, plastic, canvas or similar material of known area, volume, and weight. The spreader shall pass over the receptacle and spread the chemical at the anticipated rate. Weigh the receptacle in the field and determine the actual application rate.

b. Yield calculation based on the weigh tickets and surface area treated

Only spread lime or lime-fly ash on an area where initial mixing can be completed within 4 hours. Due to its faster reaction rate, only spread cement on an area where initial and final mixing, and compaction, can be completed within 4 hours after application.

6. Initial Mixing.

A. Lime or lime-fly ash combination. Immediately after the lime or lime-fly ash combination has been spread, thoroughly mix into the subgrade by using an approved rotary pulvimixer to a depth sufficient to obtain a final compacted layer thickness as shown on the plans. Add sufficient water to raise the moisture content of the soil mixture to three to five percent above the optimum moisture content. Continue mixing until the lime or lime-fly ash combination has been uniformly incorporated into the subgrade to the required depth with the mixture being homogeneous and friable. Complete this initial mixing within 4 hours of spreading the lime or lime-fly ash. Mellow the mixture for a minimum of 24 hours, or as reported in the mix design.

Use of Moisture Conditioned Fly Ash. The use of moisture conditioned fly ash (Class F only) for the lime-fly ash combination of soil stabilization is acceptable. Moisture conditioned fly ash will contain no more than 15 percent moisture by dry weight of fly ash. When moisture conditioned fly ash is used, ensure the lime and fly ash is spread in two separate applications and the following procedures apply:

i. Add the lime to the subgrade and mix in accordance with subsection e.6 Initial Mixing of this special provision. Once the lime is thoroughly mixed, compact the subgrade with a steel wheeled roller to achieve the surface strength and smoothness required to spread the moisture conditioned fly ash.

ii. Mellow the mixture for a minimum of 24 hours, or as reported in the mix design. Uniformly spread the moisture conditioned fly ash onto the lime treated soil to provide the equivalent dry weight basis content of fly ash as determined by the Contractor designed mix. Ensure the soil is thoroughly remixed to blend the moisture conditioned fly ash homogeneously with the lime treated soil.

B. Cement. Immediately after the chemical has been spread, mix into the subgrade soil using a rotary pulvimixer to a depth sufficient to obtain a final compacted layer thickness shown on the plans. Do not add water during the initial mixing unless the initial and final mixing will be combined into one operation according to Section 7.B. Continue mixing until the chemical has been uniformly incorporated into the subgrade to the required depth with the mixture being homogenous and friable.

C. Lime-cement combination.

i. Add the lime to the subgrade and mix in accordance with subsection e.6 Initial Mixing of this special provision. Once the lime is thoroughly mixed, compact the subgrade with a steel wheeled roller to achieve the surface strength and smoothness required to spread cement.

ii. Mellow the mixture for a minimum of 24 hours, or as reported in the mix design. Uniformly spread cement onto the lime treated soil to provide the equivalent dry weight basis content of cement as determined by the Contractor designed mix. Ensure the soil is thoroughly remixed to blend cement homogeneously with the lime treated soil. Once cement is placed as described, the stabilization process must continue in accordance with subsection e.6 Initial Mixing.

The Engineer may run field gradation testing to determine the adequacy of mixing. To determine the adequacy of the mixing, two control sieves, 1 inch and No. 4, will be used. All soil clods must pass the 1-inch sieve and at least 60 percent must pass the No. 4 sieve, exclusive of rock particles. Mixing must continue until the required gradation is achieved.

7. Final Mixing.

A. Lime or lime-fly ash combination. After the required mellowing period from the mix design, remix the soil, adding water as needed to raise the moisture content two to three percent above optimum. Continue mixing until the lime or lime-fly ash combination has been uniformly incorporated into the subgrade to the required depth and with soil clods broken down to pass a 1-inch screen and at least 60 percent passing the No. 4 sieve, exclusive of rock particles. Ensure there are no un-hydrated lime particles present before compaction operations start. The Engineer will verify that any visible particles are not un-hydrated lime before compaction begins. The Engineer may run field gradation testing to determine the adequacy of mixing.

B. Cement and Lime-cement combination. Within 2 hours of initial mixing, remix the soil and introduce water through the mixer to bring the mixed material to at least optimum but no more than 3 percent above optimum moisture. Uniformly distribute the water in sufficient quantity to hydrate the cement. For cement only: Initial and final mixing can be combined into one step so long as the test strip demonstrated the requirements for mixing can be achieved in one step as approved by the Engineer.

It is the Contractor's responsibility to determine the in-situ moisture content of the soil or soil-chemical mixture using speedy, oven dry method, or other approved methods to determine the quantity of water required to raise the moisture content to the required level. A nuclear gauge may be used to determine the in-situ moisture content of the soils prior to treating with the chemical.

8. Compaction.

A. Lime or Lime-fly ash combination. Begin compaction immediately after final mixing and approval by the Engineer. Add water or aerate the subgrade to bring the soil-chemical mixture to optimum moisture content, plus or minus two percent. Continue compaction until the stabilized subgrade has a density of at least 95 percent of the maximum unit weight established for the soil-chemical mixture. Begin rolling at the outside edge of the surface and proceed to the center, overlapping on successive trips at least one-half width of the roller, or as determined by the Engineer based upon construction staging. At all times, the speed of the roller must not cause displacement of the mixture to occur. Ensure areas inaccessible to the rollers are compacted with mechanical tampers or other appropriate equipment, and shaped and finished by hand methods as needed.

Perform final compaction with steel-wheeled smooth drum rollers. Shape, fine grade and compact within the subgrade tolerances in accordance with the standard specifications. The Engineer will perform the density, moisture, and Dynamic Cone Penetrometer (DCP) testing for the compacted subgrade for acceptance in accordance with this special provision and the standard specifications.

For failing density tests within 72 hours after compaction, rework and recompact to achieve the required density. For failing density tests more than 72 hours after compaction, refer to section e.11.

B. Cement or Lime-cement combination. Begin compaction immediately after final mixing and approval by the Engineer. Compact the cement-treated mixture in one lift and complete compaction within 2 hours after final mixing. Add water or aerate the subgrade to bring the soil-chemical mixture to optimum moisture content, plus or minus two percent. Continue final compaction until the stabilized subgrade has a density of at least 95 percent of the maximum unit weight established for the soil-chemical mixture. Begin rolling at the outside edge of the surface and proceed to the center, overlapping on successive trips at least one-half width of the roller, or as determined by the Engineer based upon construction staging. At all times, the speed of the roller must not cause displacement of the mixture to occur. Ensure areas inaccessible to the rollers are compacted with mechanical tampers or other appropriate equipment, and shaped and finished by hand methods as needed.

Perform final compaction with steel-wheeled smooth drum rollers. Shape, fine grade and compact within the subgrade tolerances in accordance with the standard specifications. The Engineer will perform the density, moisture, and Dynamic Cone Penetrometer (DCP) testing for the compacted subgrade for acceptance in accordance with this special provision and the standard specifications (section h).

9. Finishing. Immediately after compaction, shape, and fine grade the surface of the treated material to conform with the typical sections shown on the plans. Remove loosened material and dispose of at an approved location. Roll the finished surface immediately, adding water by sprinkling as needed during rolling. Use smooth-drum steel wheel rollers during finishing.

10. Curing and Protection. Immediately after the stabilized subgrade has been compacted and finished, protect the surface against rapid drying for 5 days by periodic (when about 1/3 of the surface area no longer appears moist) sprinkling with water or by placing a curing coat of asphalt emulsion. If a curing coat is used, apply asphalt emulsion at a rate of 1 gallon per 30 square feet. Other suitable methods of curing the compacted stabilized soil mix may be utilized as approved by the Engineer.

    Completed portions of stabilized subgrade may be opened immediately to light construction traffic at the Contractor’s own risk and option, provided the curing is not impaired. After the curing period has elapsed, completed areas may be opened to construction traffic to commence placement of subsequent pavement layers. Placement of subsequent pavement layers may begin the day following the completion of stabilization only if the completed stabilized area has strengthened sufficiently. The strength of completed stabilized areas can be evaluated using proof rolling or dynamic cone penetrometer (DCP) testing. Proof rolling can be performed using a loaded tandem axle truck (with a minimum 24 tons of gross vehicle weight) driving at walking speed. After one pass of the proof rolling truck, the observations of the subgrade should not show any pumping, cracking, or more than 0.5” of deflection or deformation. DCP test results should meet the requirements of Table 6. Protect finished portions of stabilized subgrade sections from marring and damaging of the completed work. The Contractor is responsible for correcting and restabilizing damaged areas as determined by the Engineer at no cost to the contract.

    Do not allow the treated subgrade to freeze during the curing period prior to placing subsequent layers. If the treated subgrade is not covered with base or pavement and is subjected to freezing, add additional stabilizer and re-compact the treated subgrade before placing any subsequent layers. The Engineer, with the consultation of contractor’s mix design consultant, will determine the additional quantity of stabilizer to add, if any, and the extent of re-compaction.

11. Restabilization. If an approved stabilized area shows failure, tenderness, or damage after curing, or areas with failed density testing, the Engineer will require restabilization to be performed, where appropriate, at no additional cost to the contract. The Engineer, with the consultation of contractor's mix design consultant, will determine the additional quantity of stabilizer to add and the extent of re-stabilization.

    a. Lime or Lime-flyash: When an area is restabilized more than 72 hours after compaction, add 25% of the mix design lime or lime-fly ash rate when restabilizing, unless otherwise approved.
    b. Cement or Lime-cement: When an area fails to meet density requirements, and 2 hours has passed after final mixing, remove and replace the material and/or re-stabilize the section by adding the mix design cement content, remixing, and recompacting, to provide the required density, as directed or approved by the Engineer.

f. Field Quality Control. Results of field QC testing must verify that the materials and procedures comply with this special provision and the standard specifications. Perform field quality control testing during the treatment process in accordance with Table 4 at locations independent from the Engineer's testing locations, unless otherwise directed. Test results from field quality control will not be used for acceptance. The contractor may perform additional testing as they deem necessary for field quality control. Report test results and all pertinent information to the Engineer. When test results do not meet specification requirements, modify operations and perform the test methods required in Table 4. Suspend operations when any of the test results performed after the modifications do not meet specification requirements. Perform all field quality control tests in the presence of the Engineer or the Engineer's designated representative.

Table 4. Field quality control tests

Test Type	Testing requirement
Chemical application rate	1 test per 4,000 square yards or at least once per day
Field moisture content	1 test per 4,000 square yards or at least once per day
Stabilized layer thickness	3 tests per 4,000 square yards or at least once per day

Ensure completed thickness of the chemically stabilized subgrade soil layer is not less than 1/2 inch of the specified thickness.

Where the measured thickness of the stabilized subgrade layer is thicker than required, the stabilized layer will be considered conforming to the specified thickness, provided the elevation of finished subgrade is within the tolerance specified in the standard specifications.

Stabilized layer thickness will be measured in three-inch diameter or larger test holes penetrating the stabilized subgrade. Apply a phenolphthalein solution to the cut surface as an aid to determine the presence of stabilizing agent.

h. Field Quality Assurance. The Engineer will perform chemical application rate, field moisture content, field density, stabilized layer thickness, and DCP tests in accordance with Table 5 to verify that the required depth of subgrade is uniformly stabilized and compacted.

Table 5. Field quality assurance tests

Test Type	Testing requirement
Chemical application rate	1 test per per day
Field moisture content	1 test per 4,000 square yards or at least once per day
Stabilized layer thickness	3 tests per 4,000 square yards or at least once per day
Field Density	1 per 4,000 square yards or at least once per day
DCP	1 per 4,000 square yards or at least once per day

Stabilized layer thickness and DCP test. The Engineer or Engineer's representative will use a DCP or three-inch diameter or larger test holes to verify that the minimum thickness shown on the plans has been uniformly stabilized and compacted. The Engineer will evaluate the stabilized thickness and field-stabilized subgrade strength in accordance with ASTM D6951. A maximum average DCP rate of 14 mm/blow in the stabilized zone is required for acceptance. Table 6 provides the minimum number of DCP blows in the stabilized zone for acceptance based on the thickness of the stabilized layer.

Table 6. Minimum number of DCP blows for different stabilized layer thicknesses

Stabilized Layer Thickness (inches)	Minimum Number of DCP Blows in the Stabilized Zone (after 1 seating drop)
8	15
12	22
18	33

The DCP test should start on the top of the stabilized subgrade and use 1 seating drop to properly seat the DCP tip before recording cumulative penetration values.

Correct areas where the average DCP rate is more than 14 mm/blow by scarifying, adding additional chemical, remixing and re-compacting as directed by the Engineer. All corrections must be completed with no additional cost to the contract.

When the measured thickness of the stabilized subgrade soil is more than 1/2 inch deficient follow the following steps:

- **For lime or lime-fly ash stabilized subgrade -** correct deficient areas by scarifying, adding additional chemical, remixing and recompacting as directed by the Engineer.
- **For cement or lime-cement stabilized subgrade** – correct deficient areas by scarifying, adding the mix-design chemical amount, remixing and compacting as directed by the Engineer.

Field density test. The Engineer will perform density tests at a rate of 1 per every 4,000 square yards or at least 1 per day. The nuclear density gauge will be used to measure the wet density but will not be used to measure the moisture content. The Engineer will use the "Speedy" moisture gauge or other approved methods to measure the moisture content to calculate the dry density. The Engineer will use a multi-point density curve from the mix design developed by the contractor to obtain the maximum dry density and optimum moisture content. One-point density curve will not be allowed to obtain the maximum dry density.

i. Measurement and Payment. The completed work, as described, will be measured and paid for at the contract unit price using the following pay items:

Pay Item	**Pay Unit**
Chemically Stabilized Subgrade	Square Yard
Lime	Ton
Fly ash	Ton
Cement, Special	Ton

1. **Chemically Stabilized Subgrade**,
Chemically stabilized subgrade, as completed to the thickness and cross sections shown on the plans, will be measured in square yards of horizontal surface area based on in place quantity. All calculations of areas measured for payment must be based on measurements made to the nearest 0.1 yard with area calculated to the nearest square yard. The length will be measured along the surface of the completed roadbed parallel to the centerline. The width will be the top surface width of the completed roadbed specified on the plans, measured perpendicular to the center line of the roadbed at 100-feet intervals. Additional areas required by the contract will be measured by length and width along the surface area stabilized.
Chemically Stabilized Subgrade includes sampling, mix design of cement, lime, lime-cement or lime-fly ash combination soil mixture(s), test strip(s), preparing subgrade, scarifying, pulverizing, mixing, shaping, water, curing, asphalt emulsion, compaction, maintaining, and application of cement, lime and fly ash, testing, including all labor, and equipment necessary to complete the work as described.

2. **Cement, Special, Lime** and **Fly Ash** incorporated into the work will be measured in tons. Payment includes furnishing, transporting, storing, handling, and spreading, including all labor, equipment, and materials necessary to complete the work as described. Furnish certified delivery tickets to the Engineer for cement, lime and fly ash incorporated into the stabilized subgrade for payment. The tickets must contain project number, material type, date, time, truck identifier number, tare weight, gross weight, net weight, supplier name and source location.

APPENDIX F: AASHTOWARE PAVEMENT ME ANALYSIS RESULTS

63022-124103_I96_HMA RECON_1_9.5_unstab_CL

File Name: C:\NB\Pavement ME\Analysis\New HMA Designs\124103_MI\63022-124103_I96_HMA RECON_1_9.5_unstab_CL.dgpx

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: July, 2023
Pavement construction: August, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42.665, -83.418

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	4EMH_64-22	2.0
Flexible	3EMH_64-22	3.3
Flexible	2EMH_58-22	4.3
NonStabilized	OGDC	16.0
NonStabilized	Sand Subbase	8.0
Subgrade	CL	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	11.5
Air voids (%)	6.1

Traffic

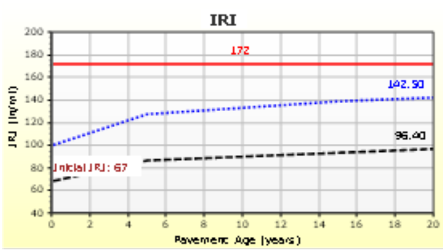
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	8,480
2033 (10 years)	11,459,500
2043 (20 years)	23,267,500

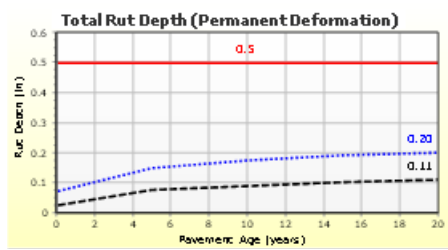
Design Outputs

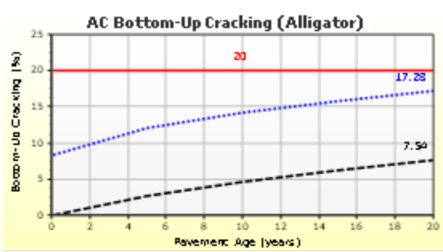
Distress Prediction Summary

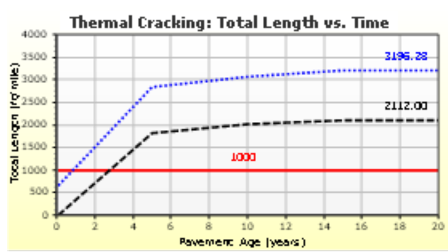
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	142.49	95.00	99.65	Pass
Permanent deformation - total pavement (in)	0.50	0.20	95.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	20.00	17.28	95.00	98.23	Pass
AC thermal cracking (ft/mile)	1000.00	3196.28	95.00	4.58	Fail
AC top-down fatigue cracking (% lane area)	25.00	16.46	95.00	99.89	Pass
Permanent deformation - AC only (in)	0.50	0.18	95.00	100.00	Pass

Distress Charts







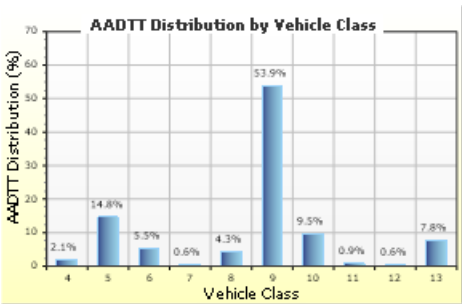


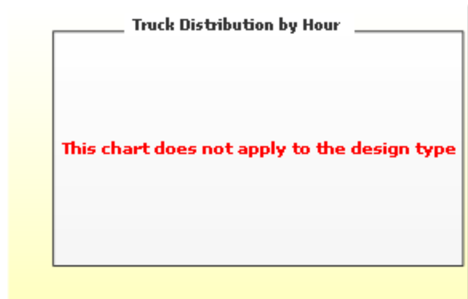
Threshold Value ····· @ Specified Reliability - - - @ 50% Reliability

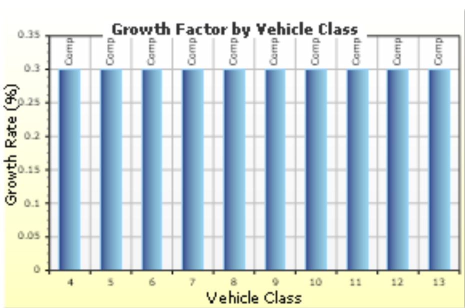
Traffic Inputs

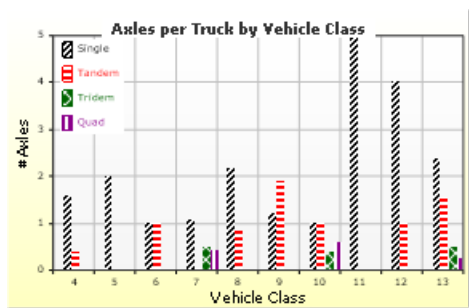
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	8,480	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	3	Percent of trucks in design lane (%):	73.0
		Operational speed (mph)	65.0

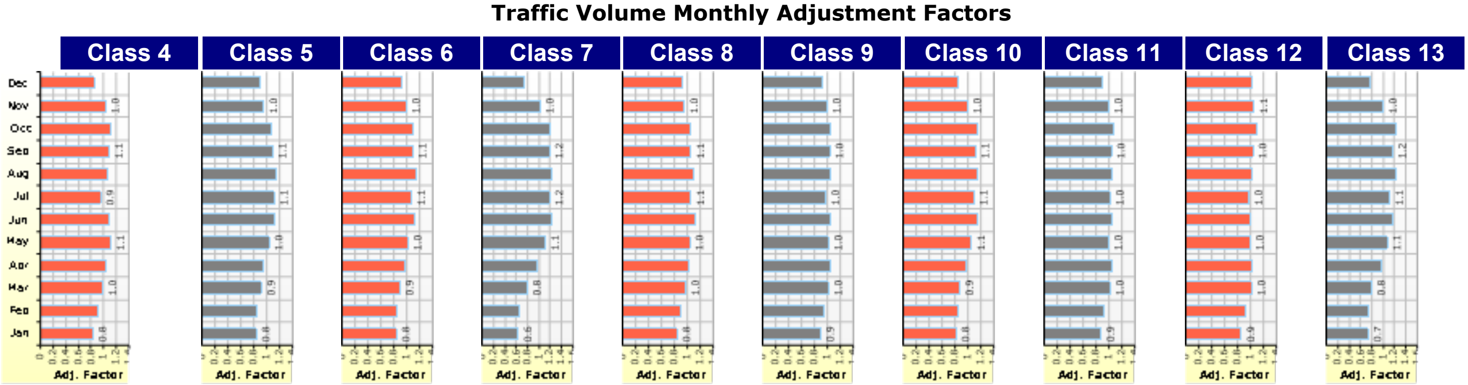








Traffic Volume Monthly Adjustment Factors



63022-124103_I96_HMA RECON_1_9.5_unstab_CL

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Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	0.8	0.8	0.8	0.6	0.8	0.9	0.8	0.9	0.9	0.7
February	0.9	0.8	0.8	0.6	0.9	0.9	0.8	0.9	0.9	0.7
March	1.0	0.9	0.9	0.8	1.0	1.0	0.9	1.0	1.0	0.8
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
May	1.1	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.1
June	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.1	1.0	1.2
July	0.9	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.1
August	1.1	1.2	1.1	1.2	1.1	1.1	1.2	1.1	1.0	1.2
September	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.2
October	1.1	1.1	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.2
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0
December	0.8	0.9	0.9	0.8	0.9	0.9	0.8	0.9	1.0	0.8

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	2.1%	0.3%	Compound
Class 5	14.8%	0.3%	Compound
Class 6	5.5%	0.3%	Compound
Class 7	0.6%	0.3%	Compound
Class 8	4.3%	0.3%	Compound
Class 9	53.9%	0.3%	Compound
Class 10	9.5%	0.3%	Compound
Class 11	0.9%	0.3%	Compound
Class 12	0.6%	0.3%	Compound
Class 13	7.8%	0.3%	Compound

Truck Distribution by Hour does not apply

Axle Configuration

Traffic Wander	
Mean wheel location (in)	18.0
Traffic wander standard deviation (in)	10.0
Design lane width (ft)	12.0

Axle Configuration	
Average axle width (ft)	8.5
Dual tire spacing (in)	12.0
Tire pressure (psi)	120.0

Average Axle Spacing	
Tandem axle spacing (in)	51.6
Tridem axle spacing (in)	49.2
Quad axle spacing (in)	49.2

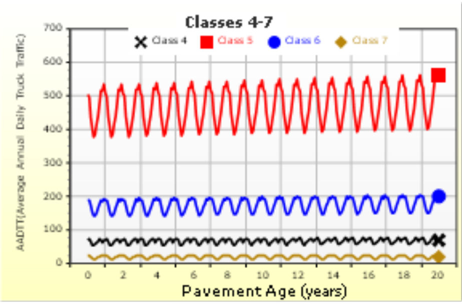
Wheelbase does not apply

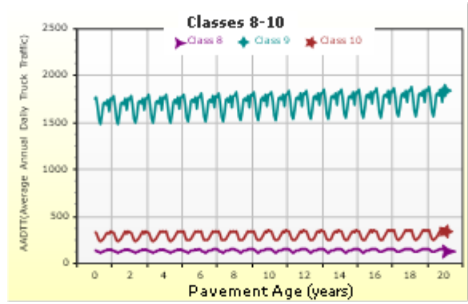
Number of Axles per Truck

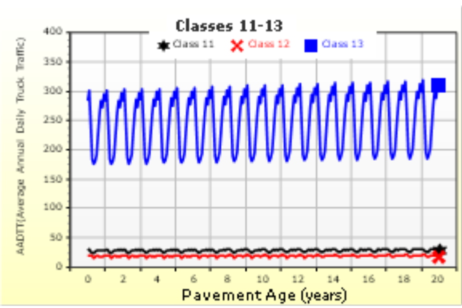
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.6	0.4	0	0
Class 5	2	0	0	0
Class 6	1	1	0	0
Class 7	1.08	0.06	0.51	0.43
Class 8	2.16	0.84	0	0
Class 9	1.21	1.89	0	0
Class 10	1	1	0.4	0.6
Class 11	5	0	0	0
Class 12	4	1	0	0
Class 13	2.4	1.56	0.51	0.27

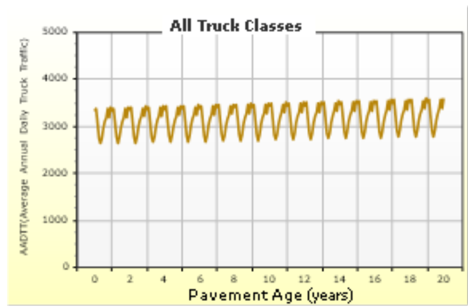
AADTT (Average Annual Daily Truck Traffic) Growth

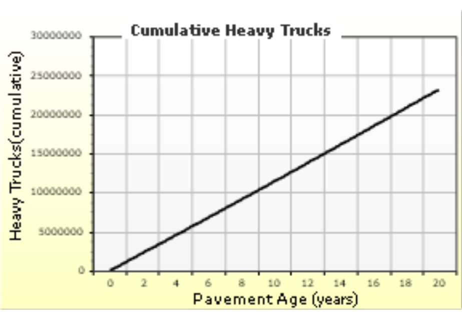
*** Traffic cap is not enforced**







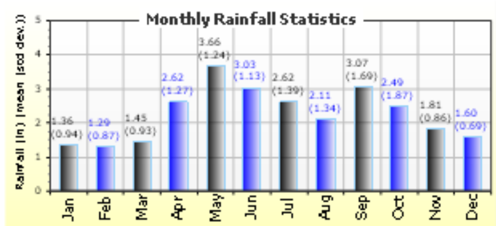




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
PONTIAC, MI	42.66500 -83.41800 971

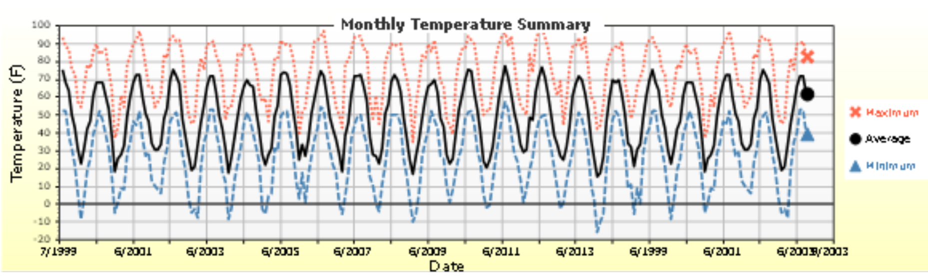


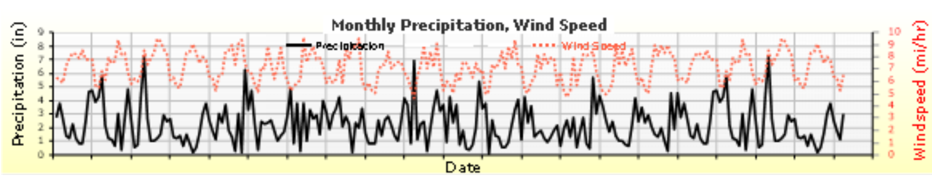
Annual Statistics:

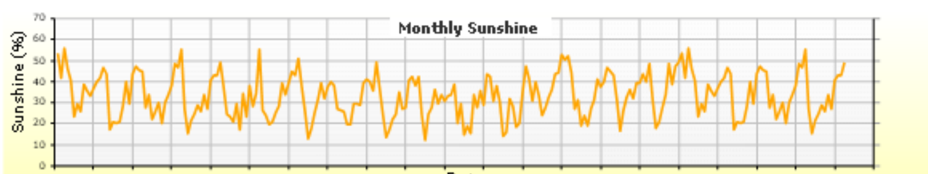
Mean annual air temperature (ºF)	49.07
Mean annual precipitation (in)	27.13
Freezing index (ºF - days)	825.94
Average annual number of freeze/thaw cycles:	57.32

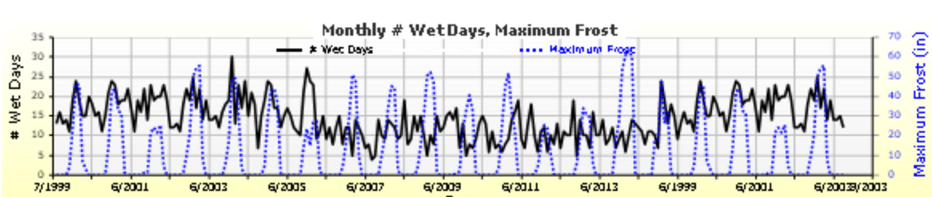
Water table depth (ft) 5.00

Monthly Climate Summary:

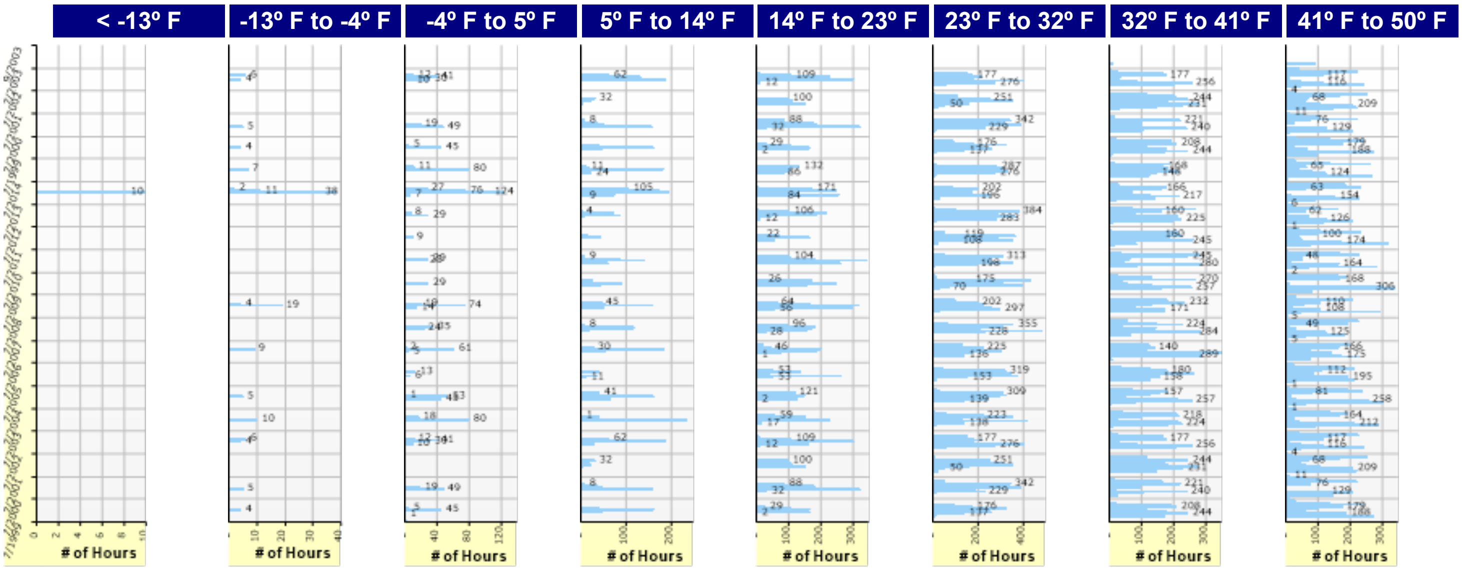


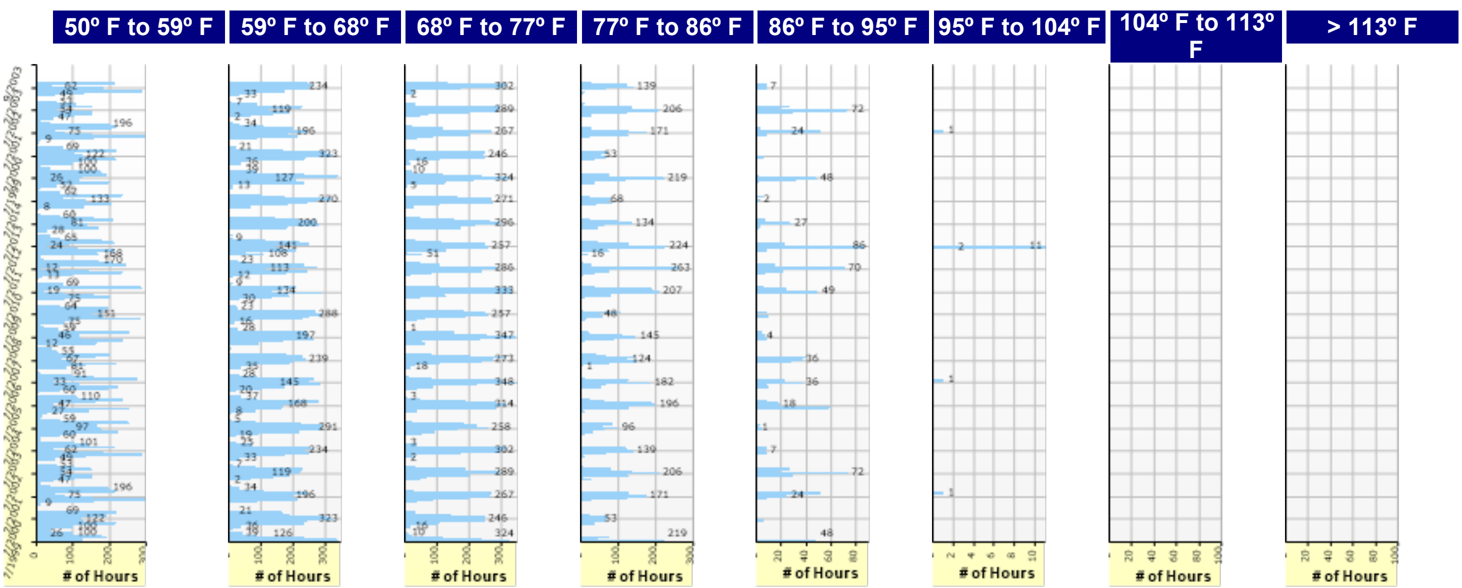






Hourly Air Temperature Distribution by Month:





Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

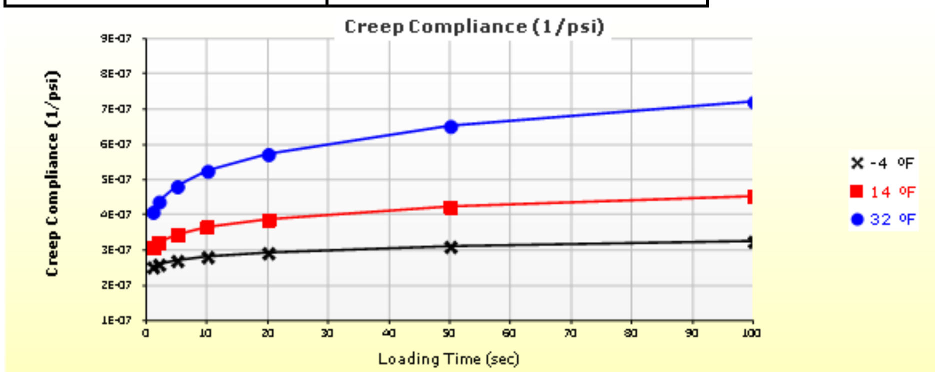
Layer Name	**Layer Type**	**Interface Friction**
Layer 1 Flexible : 4EMH_64-22	Flexible (1)	1.00
Layer 2 Flexible : 3EMH_64-22	Flexible (1)	1.00
Layer 3 Flexible : 2EMH_58-22	Flexible (1)	1.00
Layer 4 Non-stabilized Base : OGDC	Non-stabilized Base (4)	1.00
Layer 5 Non-stabilized Base : Sand Subbase	Non-stabilized Base (4)	1.00
Layer 6 Subgrade : CL	Subgrade (5)	-

Thermal Cracking

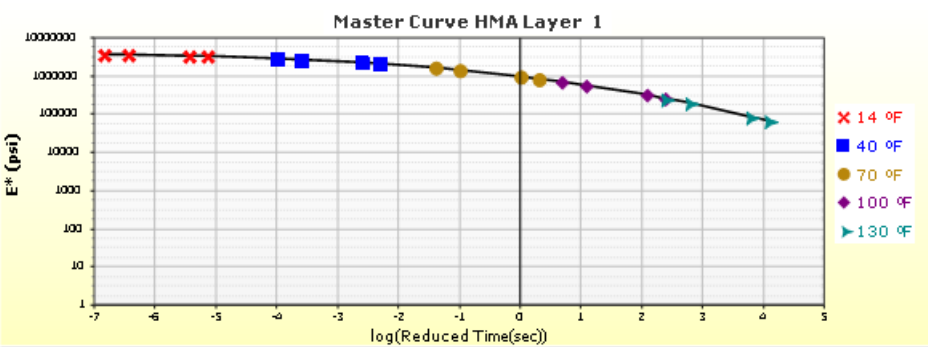
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	17.6

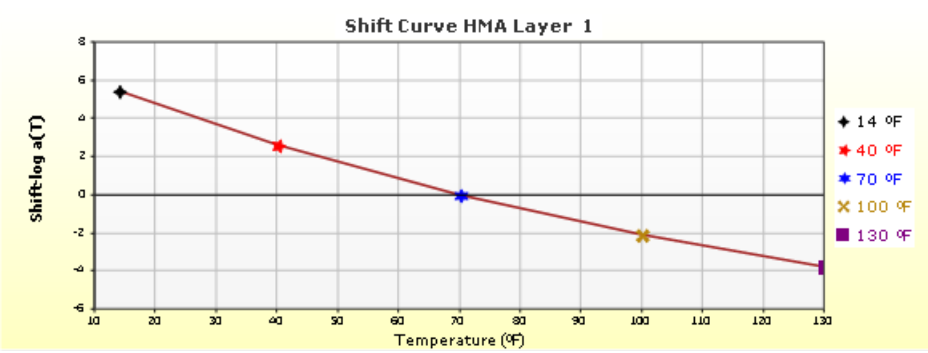
Indirect Tensile Strength (Input Level: 2)	
Test Temperature (ºF)	Indirect Tensilte Strength (psi)
14.0	575.00

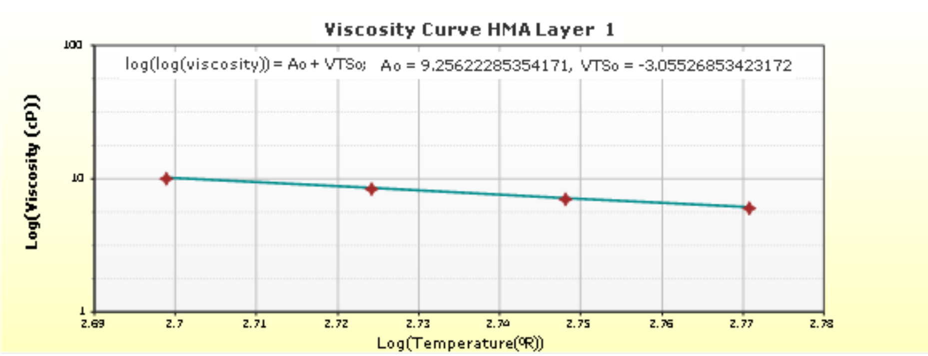
Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	-4 ºF	14 ºF	32 ºF
1	2.55e-007	3.10e-007	4.10e-007
2	2.62e-007	3.24e-007	4.40e-007
5	2.74e-007	3.46e-007	4.85e-007
10	2.83e-007	3.66e-007	5.27e-007
20	2.95e-007	3.89e-007	5.75e-007
50	3.11e-007	4.24e-007	6.53e-007
100	3.26e-007	4.55e-007	7.23e-007



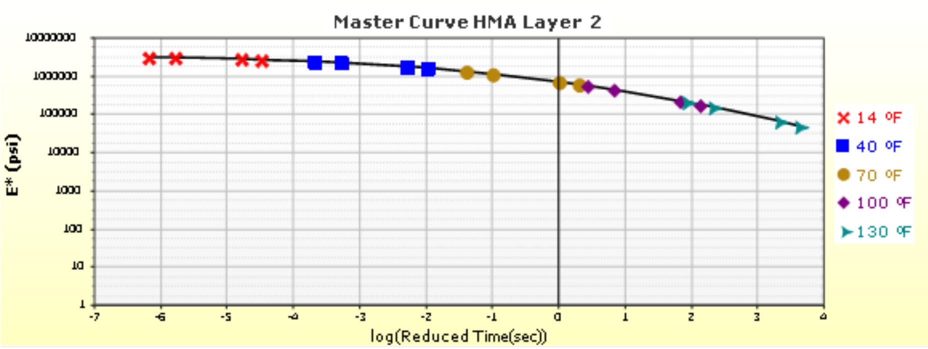
HMA Layer 1: Layer 1 Flexible : 4EMH_64-22

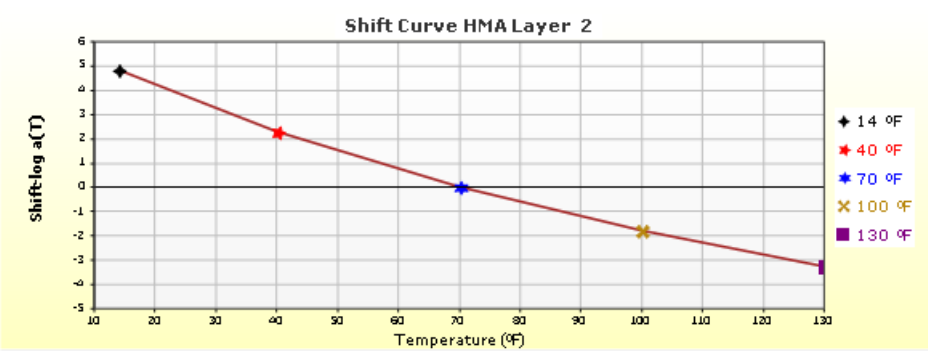


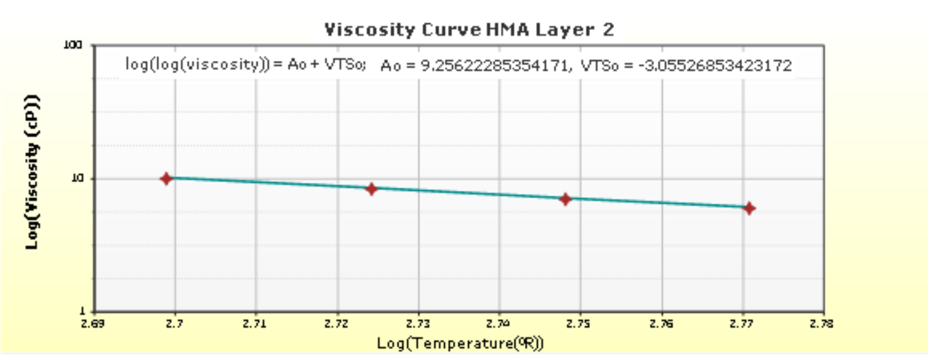




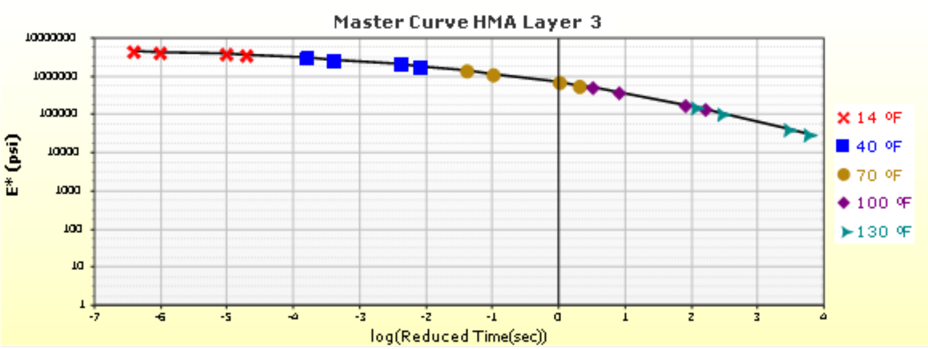
HMA Layer 2: Layer 2 Flexible : 3EMH_64-22

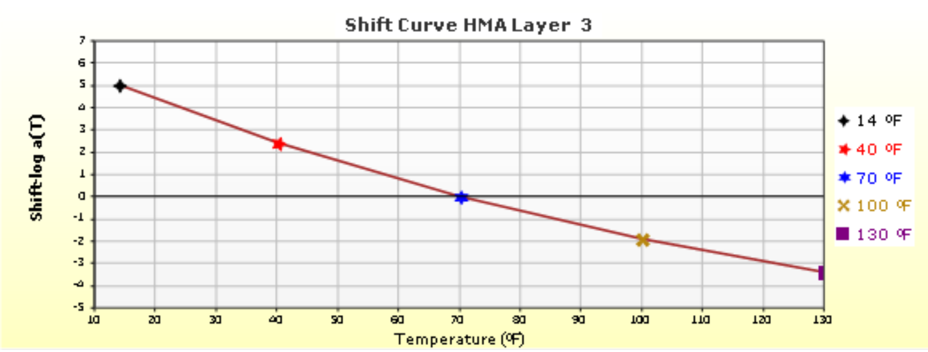


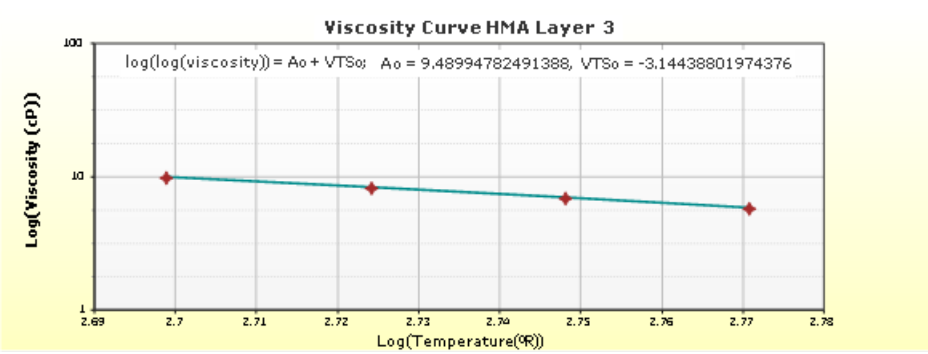




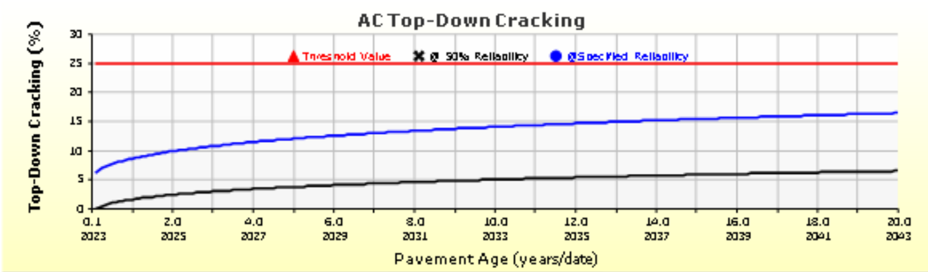
HMA Layer 3: Layer 3 Flexible : 2EMH_58-22

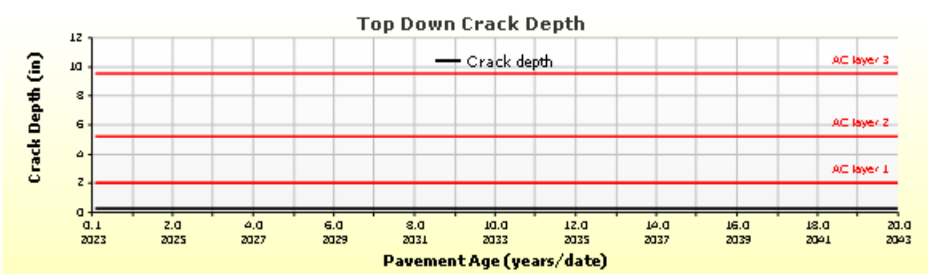


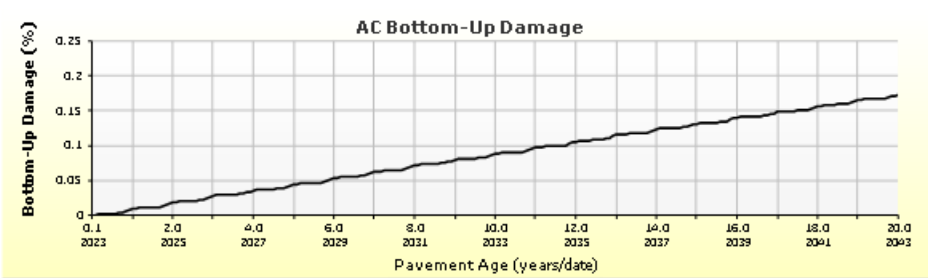


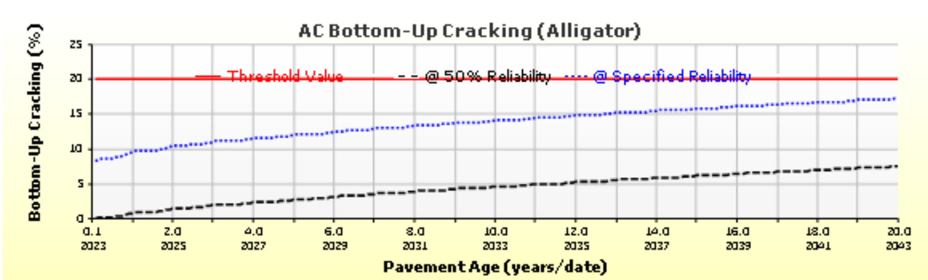


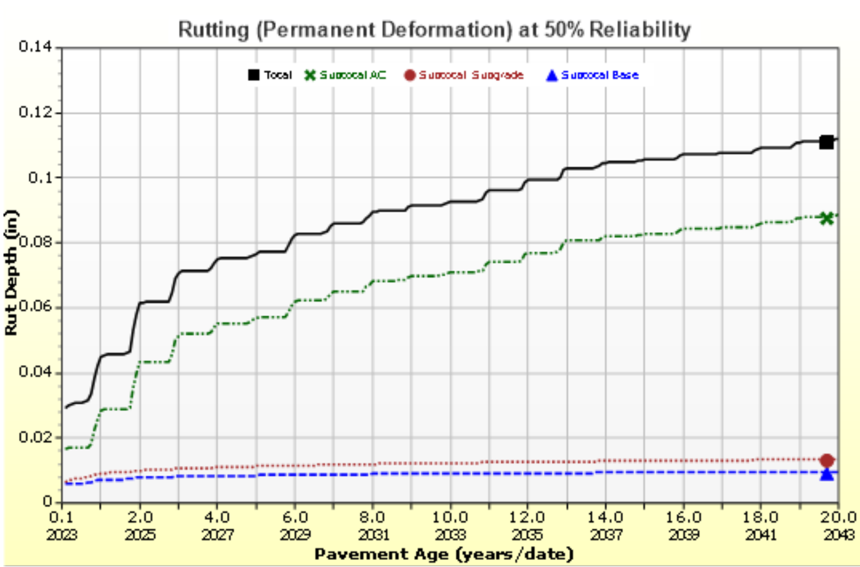
Analysis Output Charts


AC Top-Down Cracking
Threshold Value
@ 50% Reliability
@Specified Reliability
Top-Down Cracking (%)
Pavement Age (years/date)

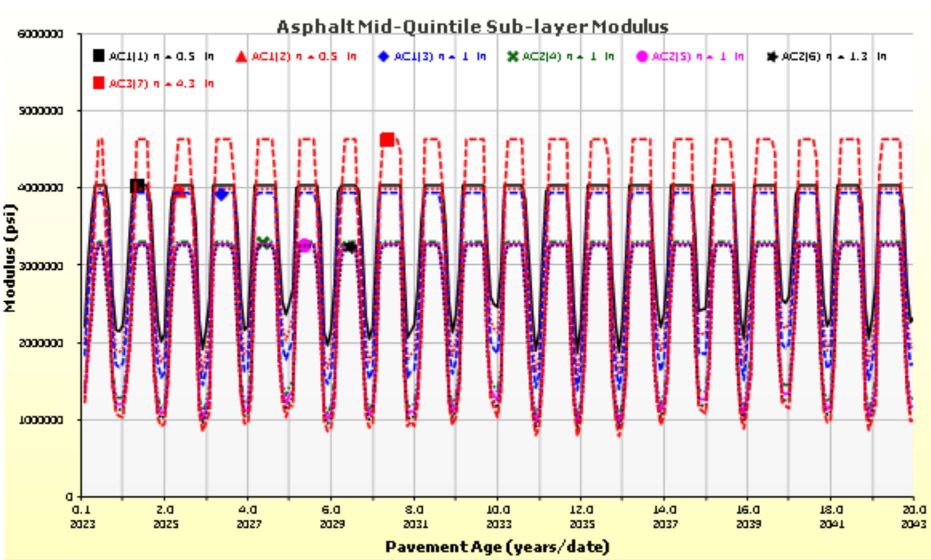

Top Down Crack Depth
Crack depth
AC layer 3
AC layer 2
AC layer 1
Crack Depth (in)
Pavement Age (years/date)


AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)

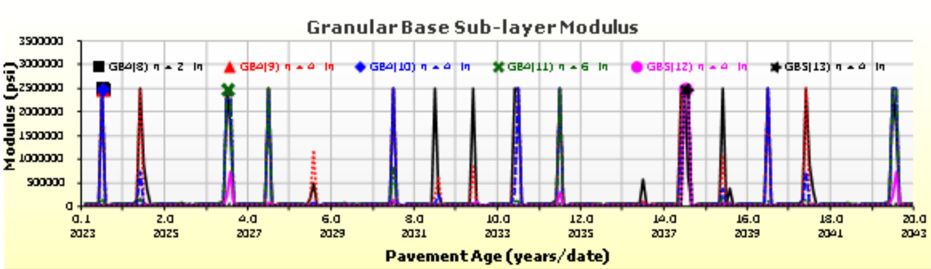

AC Bottom-Up Cracking (Alligator)
Threshold Value
@ 50% Reliability
@ Specified Reliability
Bottom-Up Cracking (%)
Pavement Age (years/date)



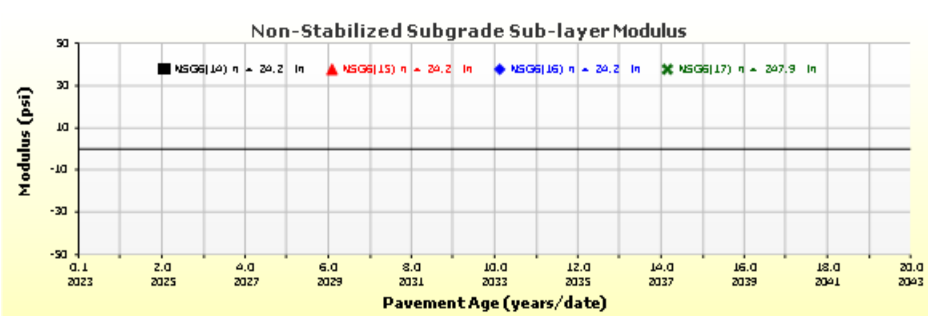
Rutting (Permanent Deformation) at 50% Reliability
Total
Subtotal AC
Subtotal Subgrade
Subtotal Base
Rut Depth (in)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)



Asphalt Mid-Quintile Sub-layer Modulus
AC1(1) h = 0.5 in
AC1(2) h = 0.5 in
AC1(3) h = 1 in
AC2(4) h = 1 in
AC2(5) h = 1 in
AC2(6) h = 1.3 in
AC3(7) h = 4.3 in
Modulus (psi)
Pavement Age (years/date)



Granular Base Sub-layer Modulus
GB4(8) h = 2 in
GB4(9) h = 4 in
GB4(10) h = 4 in
GB4(11) h = 6 in
GB5(12) h = 4 in
GB5(13) h = 4 in
Modulus (psi)
Pavement Age (years/date)



Non-Stabilized Subgrade Sub-layer Modulus
NSG6(14) h = 24.2 in
NSG6(15) h = 24.2 in
NSG6(16) h = 24.2 in
NSG6(17) h = 247.9 in
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : 4EMH_64-22

Asphalt		
Thickness (in)	2.0	
Unit weight (pcf)	146.4	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	1 Hz	10 Hz	25 Hz
14	2838283.1	3334118.2	3766841.5	3919629.2
40	1632355.7	2178796.6	2723856.9	2931877.7
70	607108.2	993384.7	1474667.7	1684561.2
100	160848.6	328113.1	599280.9	738853
130	36540.6	88188.9	194588.1	258984.5

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
40	15522432.6	46.1
70	2723528.3	58.4
100	234411.5	69
130	15452.3	77.3
168	885.3	84.4

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	11.5
Air voids (%)	6.1
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.6
Aggregate parameter	0.3313

Identifiers

Field	Value
Display name/identifier	4EMH_64-22
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	64-22
User defined field 2	Used [test] for E/IDT/Dt
User defined field 3	
Revision Number	0

Layer 2 Flexible : 3EMH_64-22

Asphalt		
Thickness (in)	3.3	
Unit weight (pcf)	147.6	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	1 Hz	10 Hz	25 Hz
14	2259900.6	2753660.7	3177786.7	3324297
40	1212821.6	1733458.7	2265760.5	2468893.6
70	410324	740397.3	1185353.4	1385958.1
100	106231	234742.3	466357.7	592731.4
130	27566.1	66765.6	154298.8	210388.3

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
40	15522432.6	46.1
70	2723528.3	58.4
100	234411.5	69
130	15452.3	77.3
168	885.3	84.4

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	10.8
Air voids (%)	5.8
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	3EMH_64-22
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	64-22
User defined field 2	Used [test] for E/IDT/Dt
User defined field 3	
Revision Number	0

Layer 3 Flexible : 2EMH_58-22

Asphalt		
Thickness (in)	4.3	
Unit weight (pcf)	151.6	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	1 Hz	10 Hz	25 Hz
40	1317170.3	1976027.7	2757154.4	3096039
70	367272.1	702162.3	1187239.3	1421849.6
100	72923.3	181766.9	394664.9	516363.8
130	14813.3	41865.3	111025.8	158519

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
40	11843112.7	47.3
70	2023700.3	59.7
100	155618.5	70.2
130	9667.5	78.3
168	610.5	84.8

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.7
Air voids (%)	4.8
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	2EMH_58-22
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	58-22
User defined field 2	Used [pred] for E/IDT/Dt
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : OGDC

Unbound	
Layer thickness (in)	16.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 2)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
33000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	OGDC
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	0.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127
Saturated hydraulic conductivity (ft/hr)	False	4.322e-01
Specific gravity of solids	False	2.7
Water Content (%)	False	6.5

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	9.6111
bf	2.9560
cf	0.8456
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	4.2
#100	
#80	
#60	
#50	
#40	
#30	13.7
#20	
#16	
#10	
#8	23.6
#4	
3/8-in.	
1/2-in.	58.8
3/4-in.	
1-in.	93.5
1 1/2-in.	100.0
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 5 Non-stabilized Base : Sand Subbase

Unbound	
Layer thickness (in)	8.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
20000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Sand Subbase
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	0.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	124.6
Saturated hydraulic conductivity (ft/hr)	False	9.427e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	9.5

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	5.4729
bf	1.9212
cf	0.8511
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	4.6
#100	15.6
#80	
#60	
#50	
#40	
#30	
#20	
#16	
#10	
#8	
#4	
3/8-in.	
1/2-in.	
3/4-in.	
1-in.	99.8
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 6 Subgrade : CL

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Annual representative values
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
4400.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	CL
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	32.5
Plasticity Index	15.2
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	113.5
Saturated hydraulic conductivity (ft/hr)	False	1.334e-05
Specific gravity of solids	False	2.7
Water Content (%)	False	16.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	103.6213
bf	0.7124
cf	0.2475
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	57.5
#100	68.3
#80	
#60	
#50	
#40	90.7
#30	
#20	96.0
#16	
#10	97.7
#8	
#4	99.5
3/8-in.	99.9
1/2-in.	
3/4-in.	
1-in.	
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Calibration Coefficients

AC Fatigue

$$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$$

k1: 3.75
k2: 2.87
k3: 1.46
Bf1: (5.014 * Pow(hac,-3.416)) * 1 + 0
Bf2: 1.38
Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_a^2 + 2.4868 * H_a - 17.342$$

$$C_2 = 0.0172 * H_a^2 - 1.7331 * H_a + 27.428$$

Where:

$H_{ac} = total\ AC\ thickness(in)$

$\varepsilon_p = plastic\ strain(in/in)$

$\varepsilon_r = resilient\ strain(in/in)$

$T = layer\ temperature(°F)$

$N = number\ of\ load\ repetitions$

acRuttingStandardDeviation	0.1481 * Pow(RUT,0.4175)	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.148 Br2:0.7 Br3:1.3
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.148 Br2:0.7 Br3:1.3
AC Layer 3	K1:-2.45 K2:3.01 K3:0.22	Br1:0.148 Br2:0.7 Br3:1.3

Thermal Fracture

$$C_f = \beta_{t1} N \left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: 0.85	Level 1 Standard Deviation: 0.1223 * THERMAL + 400.9
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1} \left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

$N_f = number\ of\ repetitions\ to\ fatigue\ cracking$

$\sigma_s = Tensile\ stress(psi)$

$M_r = modulus\ of\ rupture(psi)$

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

Unbound Layer Rutting

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

Base Rutting		Subgrade Rutting	
k1: 0.965	Bs1: 0.301	k1: 0.965	Bs1: 0.07
Standard Deviation (BASERUT) 0.0411 * Pow(BASERUT,0.3656)		Standard Deviation (BASERUT) 0.0728 * Pow(SUBRUT,0.5456)	

AC Cracking

AC Top Down Cracking

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0/2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

c1: 2.5219	c2: 0.8069	c3: 1
kL1: 64271618	kL2: 0.2855	kL3: 0.011
kL4: 0.01488	kL5: 3.266	

acCrackingTopStandardDeviation

0.3657 * TOP + 3.6563

AC Bottom Up Cracking

$$FC = \left(\frac{6000}{1 + e^{(C_1 * C_1' + C_2 * C_2' \log_{10}(D * 100))}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 0.232	c2: (0.867 + 0.2583 * hac) * 0.2204	c3: 6000

acCrackingBottomStandardDeviation

0.2262 + 14.2349/(1+exp(0.2958-0.1441*LOG10 (BOTTOM)))

CSM Cracking

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1: 0	C2: 75	C3: 2	C4: 2

csmCrackingStandardDeviation

CTB*1

IRI Flexible Pavements

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 42.874	C2: 0.102	C3: 0.0081	C4: 0.003

63022-124103_I96_HMA RECON_1_9.5_stab_CL

File Name: C:\NB\Pavement ME\Analysis\New HMA Designs\124103_MI\63022-124103_I96_HMA RECON_1_9.5_stab_CL.dgpx

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: July, 2023
Pavement construction: August, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42.665, -83.418

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	4EMH_64-22	2.0
Flexible	3EMH_64-22	3.3
Flexible	2EMH_58-22	4.3
NonStabilized	OGDC	16.0
NonStabilized	Sand Subbase	8.0
Subgrade	CL	10.0
Subgrade	CL	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	11.5
Air voids (%)	6.1

Traffic

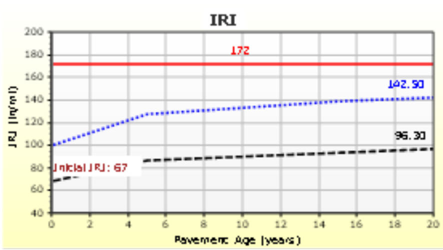
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	8,480
2033 (10 years)	11,459,500
2043 (20 years)	23,267,500

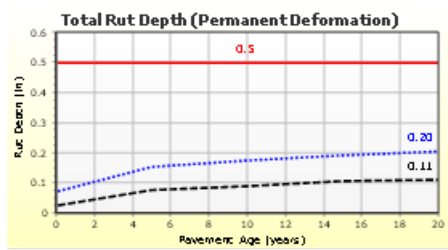
Design Outputs

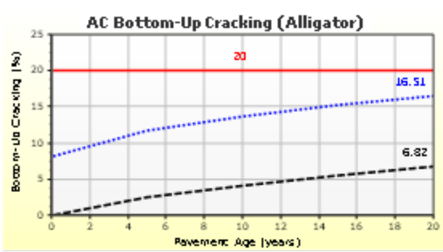
Distress Prediction Summary

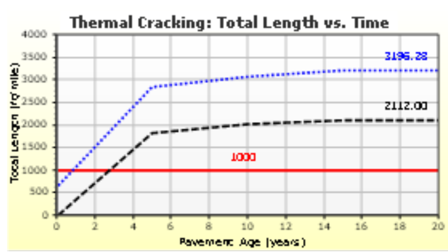
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	142.45	95.00	99.65	Pass
Permanent deformation - total pavement (in)	0.50	0.20	95.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	20.00	16.51	95.00	98.74	Pass
AC thermal cracking (ft/mile)	1000.00	3196.28	95.00	4.58	Fail
AC top-down fatigue cracking (% lane area)	25.00	16.46	95.00	99.89	Pass
Permanent deformation - AC only (in)	0.50	0.18	95.00	100.00	Pass

Distress Charts







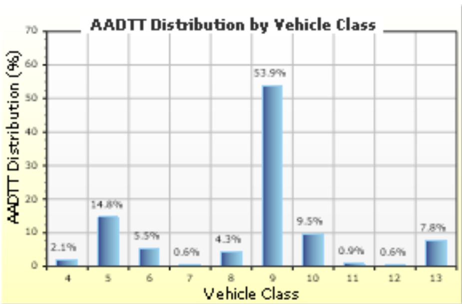


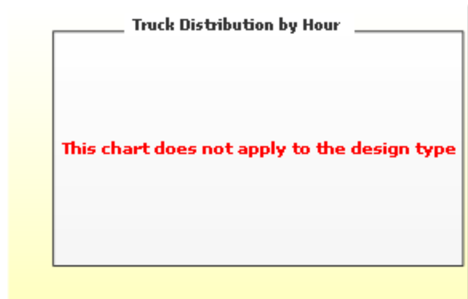
Threshold Value ····· @ Specified Reliability - - - @ 50% Reliability

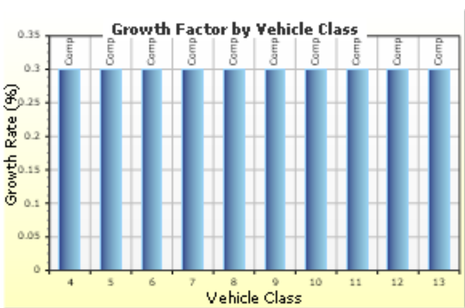
Traffic Inputs

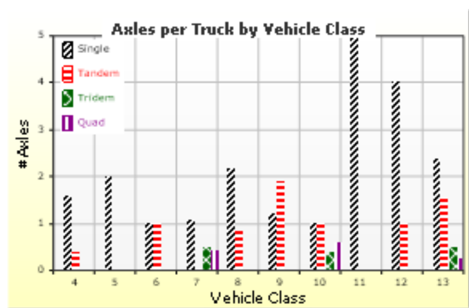
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	8,480	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	3	Percent of trucks in design lane (%):	73.0
		Operational speed (mph)	65.0

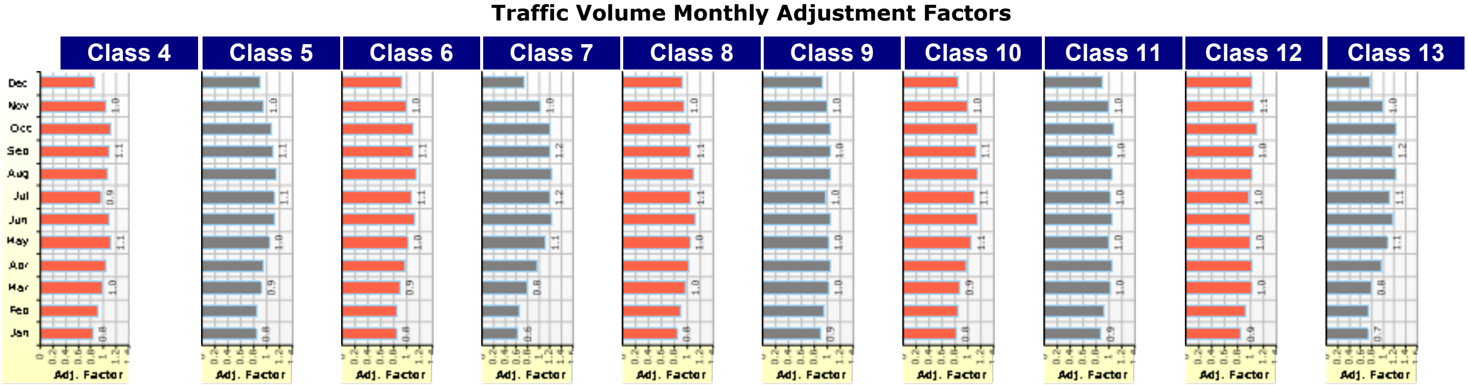








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	0.8	0.8	0.8	0.6	0.8	0.9	0.8	0.9	0.9	0.7
February	0.9	0.8	0.8	0.6	0.9	0.9	0.8	0.9	0.9	0.7
March	1.0	0.9	0.9	0.8	1.0	1.0	0.9	1.0	1.0	0.8
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
May	1.1	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.1
June	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.1	1.0	1.2
July	0.9	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.1
August	1.1	1.2	1.1	1.2	1.1	1.1	1.2	1.1	1.0	1.2
September	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.2
October	1.1	1.1	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.2
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0
December	0.8	0.9	0.9	0.8	0.9	0.9	0.8	0.9	1.0	0.8

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	2.1%	0.3%	Compound
Class 5	14.8%	0.3%	Compound
Class 6	5.5%	0.3%	Compound
Class 7	0.6%	0.3%	Compound
Class 8	4.3%	0.3%	Compound
Class 9	53.9%	0.3%	Compound
Class 10	9.5%	0.3%	Compound
Class 11	0.9%	0.3%	Compound
Class 12	0.6%	0.3%	Compound
Class 13	7.8%	0.3%	Compound

Truck Distribution by Hour does not apply

Axle Configuration

Traffic Wander	
Mean wheel location (in)	18.0
Traffic wander standard deviation (in)	10.0
Design lane width (ft)	12.0

Axle Configuration	
Average axle width (ft)	8.5
Dual tire spacing (in)	12.0
Tire pressure (psi)	120.0

Average Axle Spacing	
Tandem axle spacing (in)	51.6
Tridem axle spacing (in)	49.2
Quad axle spacing (in)	49.2

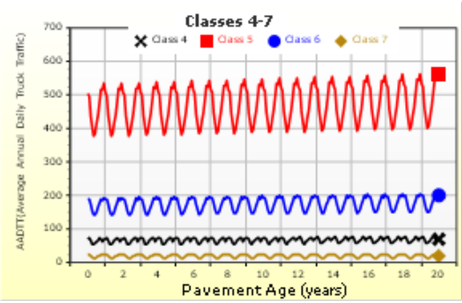
Wheelbase does not apply

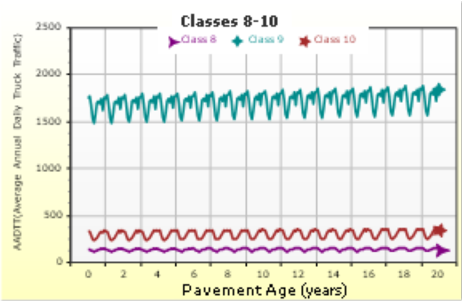
Number of Axles per Truck

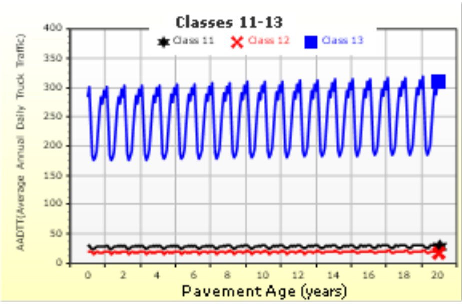
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.6	0.4	0	0
Class 5	2	0	0	0
Class 6	1	1	0	0
Class 7	1.08	0.06	0.51	0.43
Class 8	2.16	0.84	0	0
Class 9	1.21	1.89	0	0
Class 10	1	1	0.4	0.6
Class 11	5	0	0	0
Class 12	4	1	0	0
Class 13	2.4	1.56	0.51	0.27

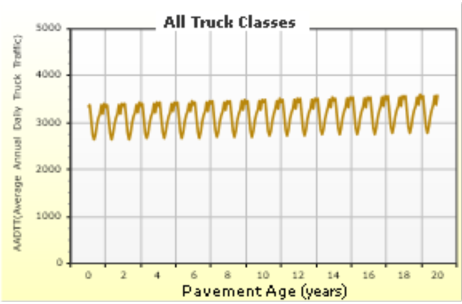
AADTT (Average Annual Daily Truck Traffic) Growth

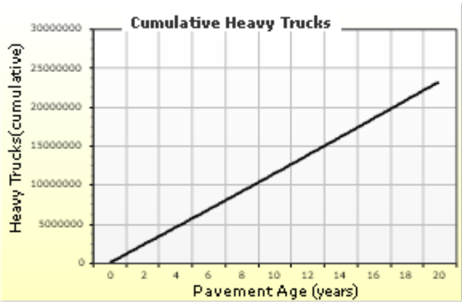
*** Traffic cap is not enforced**







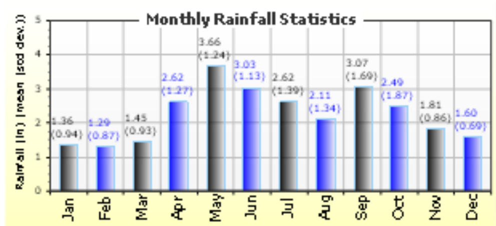




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
PONTIAC, MI	42.66500 -83.41800 971

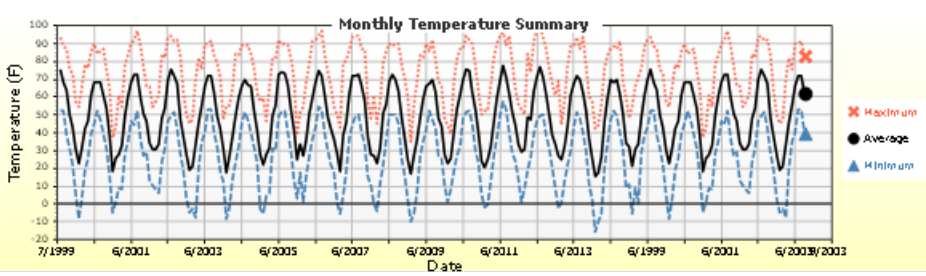


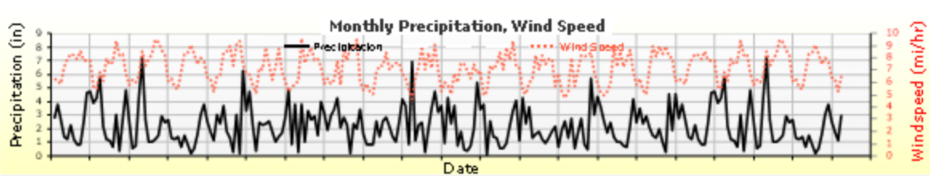
Annual Statistics:

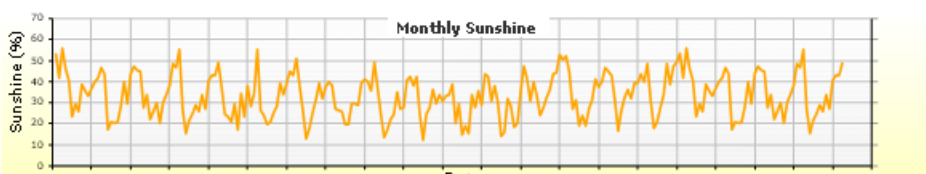
Mean annual air temperature (ºF)	49.07
Mean annual precipitation (in)	27.13
Freezing index (ºF - days)	825.94
Average annual number of freeze/thaw cycles:	57.32

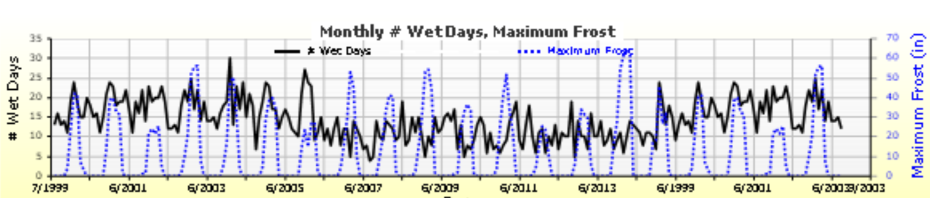
Water table depth (ft) 5.00

Monthly Climate Summary:

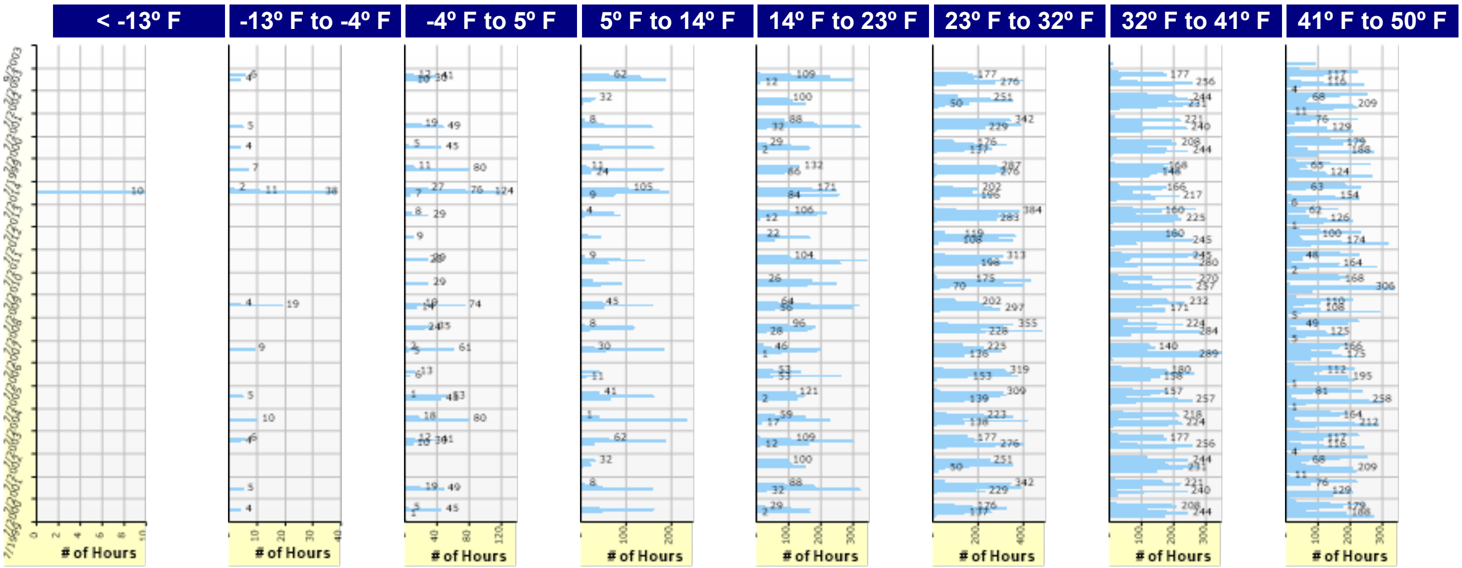


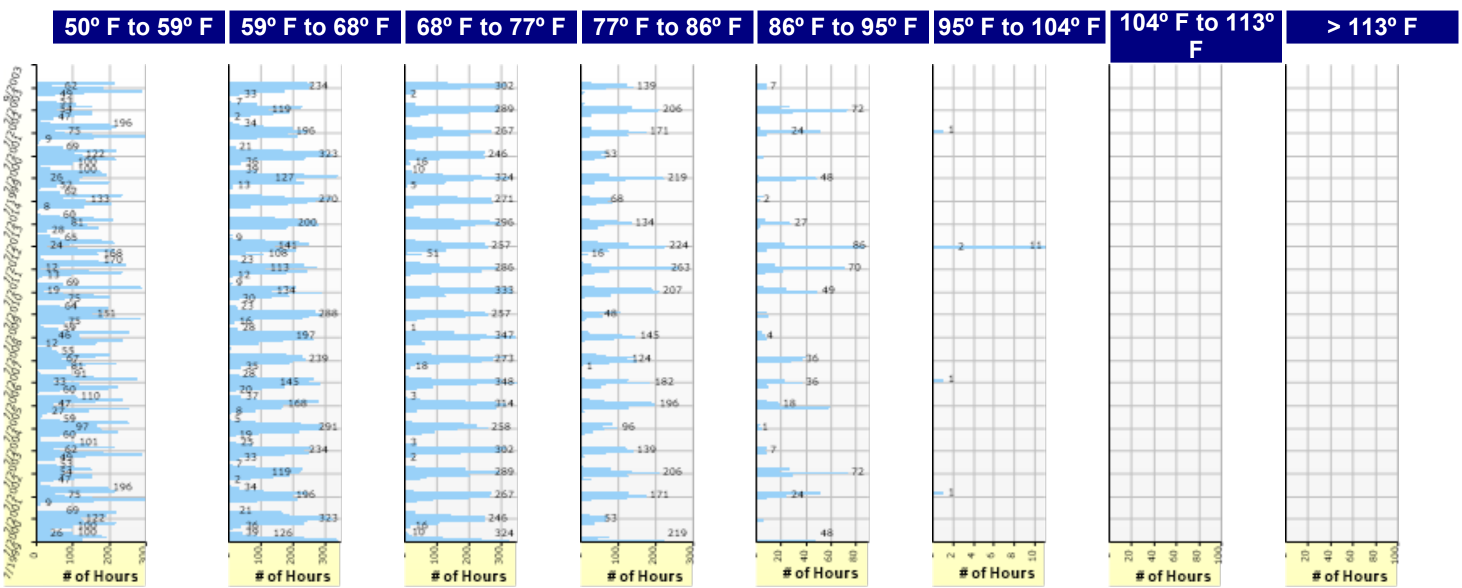






Hourly Air Temperature Distribution by Month:





Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

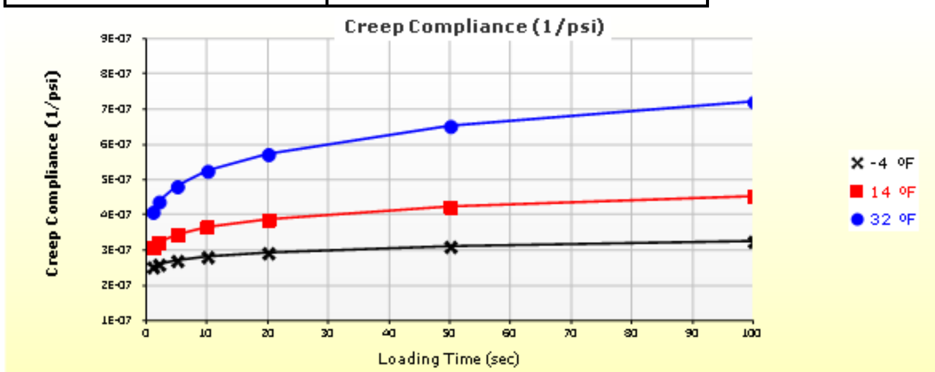
Layer Name	Layer Type	Interface Friction
Layer 1 Flexible : 4EMH_64-22	Flexible (1)	1.00
Layer 2 Flexible : 3EMH_64-22	Flexible (1)	1.00
Layer 3 Flexible : 2EMH_58-22	Flexible (1)	1.00
Layer 4 Non-stabilized Base : OGDC	Non-stabilized Base (4)	1.00
Layer 5 Non-stabilized Base : Sand Subbase	Non-stabilized Base (4)	1.00
Layer 6 Subgrade : CL	Subgrade (5)	1.00
Layer 7 Subgrade : CL	Subgrade (5)	-

Thermal Cracking

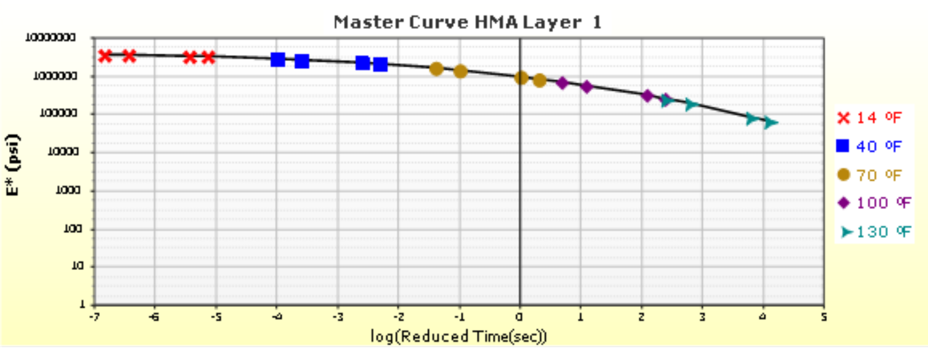
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	17.6

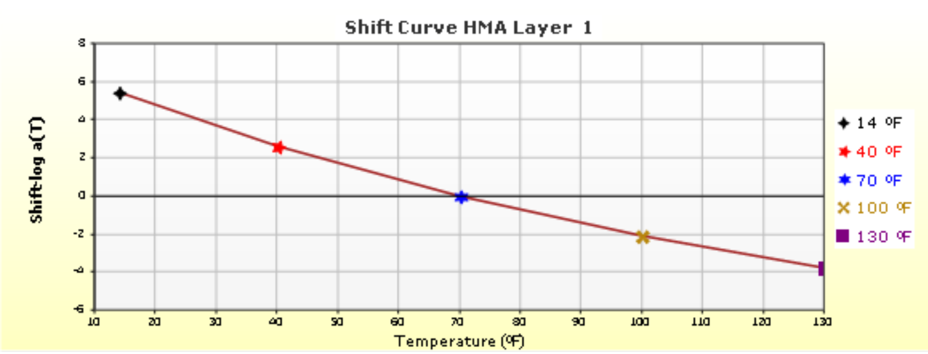
Indirect Tensile Strength (Input Level: 2)	
Test Temperature (ºF)	Indirect Tensilte Strength (psi)
14.0	575.00

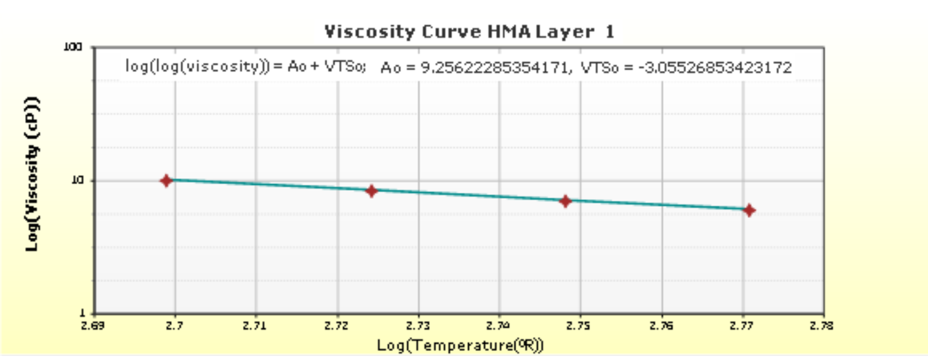
Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	-4 ºF	14 ºF	32 ºF
1	2.55e-007	3.10e-007	4.10e-007
2	2.62e-007	3.24e-007	4.40e-007
5	2.74e-007	3.46e-007	4.85e-007
10	2.83e-007	3.66e-007	5.27e-007
20	2.95e-007	3.89e-007	5.75e-007
50	3.11e-007	4.24e-007	6.53e-007
100	3.26e-007	4.55e-007	7.23e-007



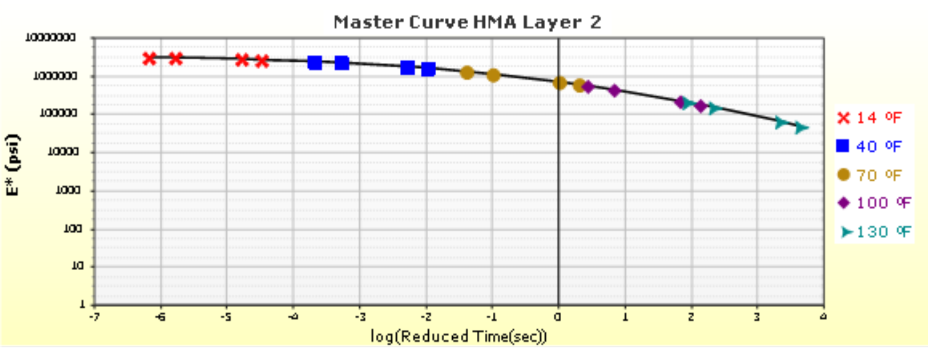
HMA Layer 1: Layer 1 Flexible : 4EMH_64-22

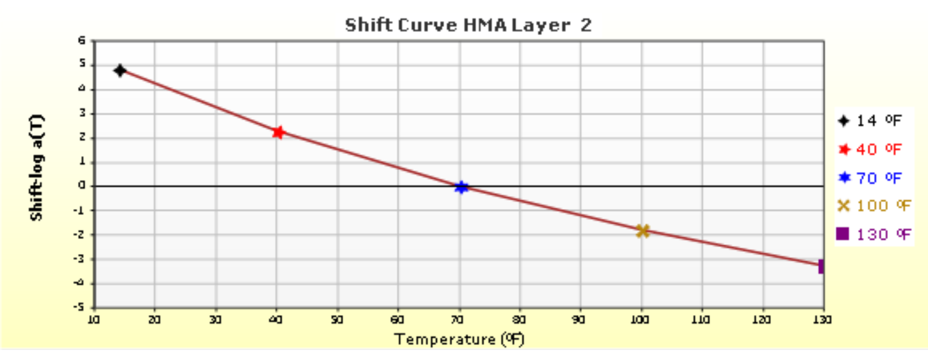


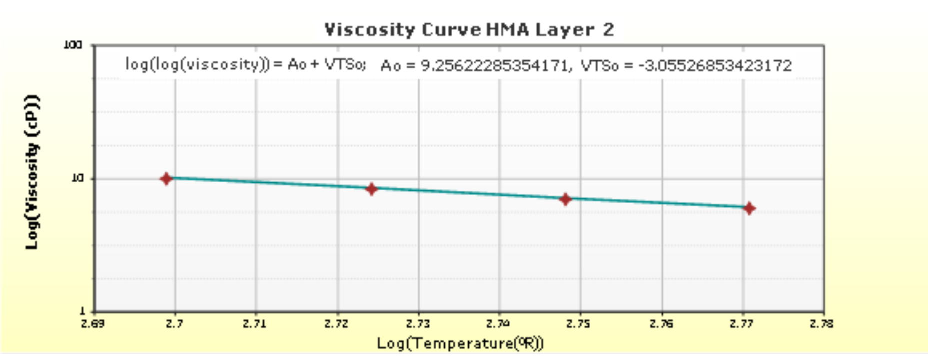




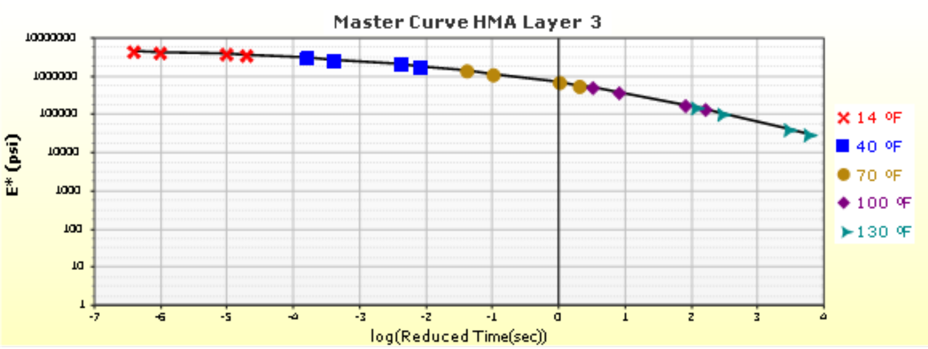
HMA Layer 2: Layer 2 Flexible : 3EMH_64-22

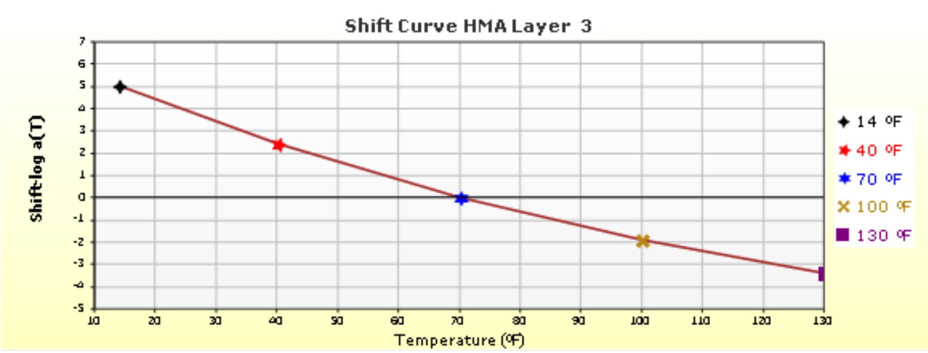


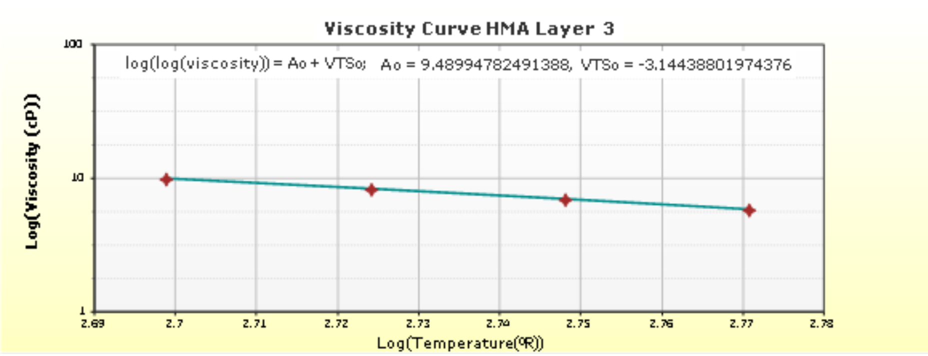




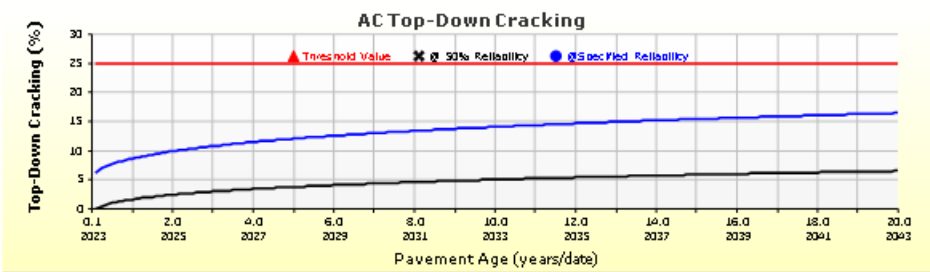
HMA Layer 3: Layer 3 Flexible : 2EMH_58-22



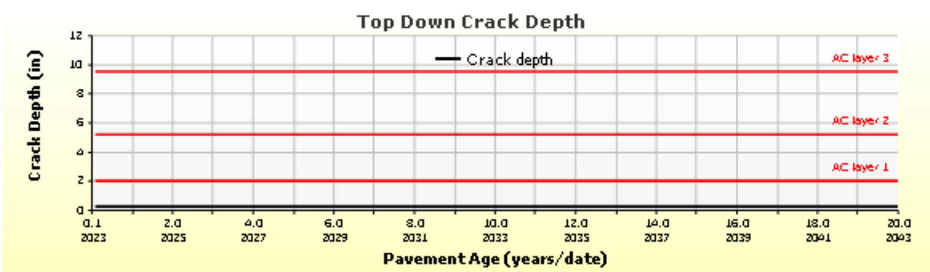




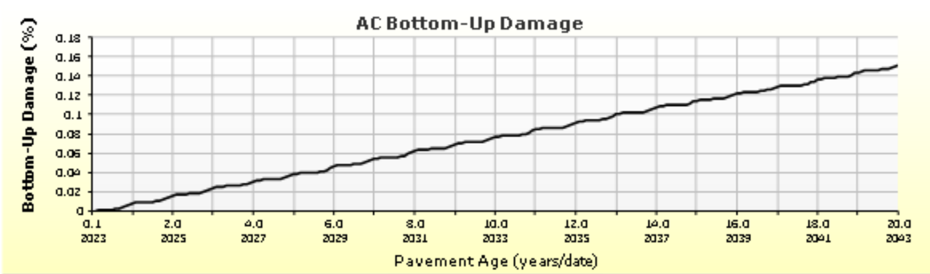
Analysis Output Charts



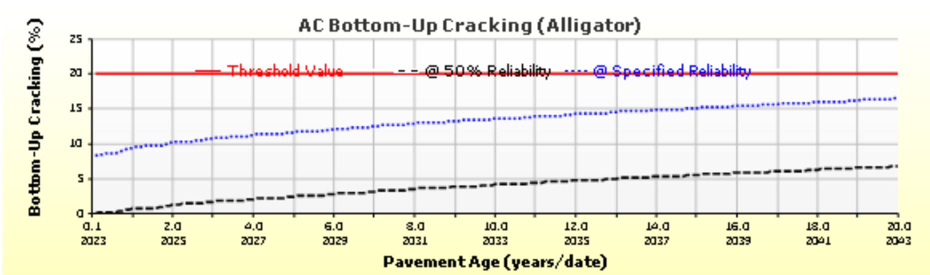
AC Top-Down Cracking
Threshold Value
@ 50% Reliability
@Specified Reliability
Top-Down Cracking (%)
Pavement Age (years/date)



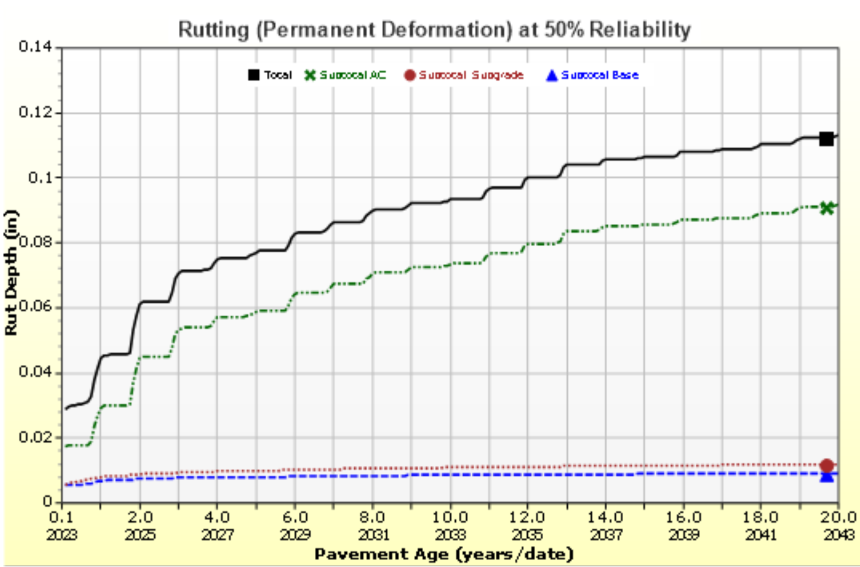
Top Down Crack Depth
Crack depth
AC layer 3
AC layer 2
AC layer 1
Crack Depth (in)
Pavement Age (years/date)

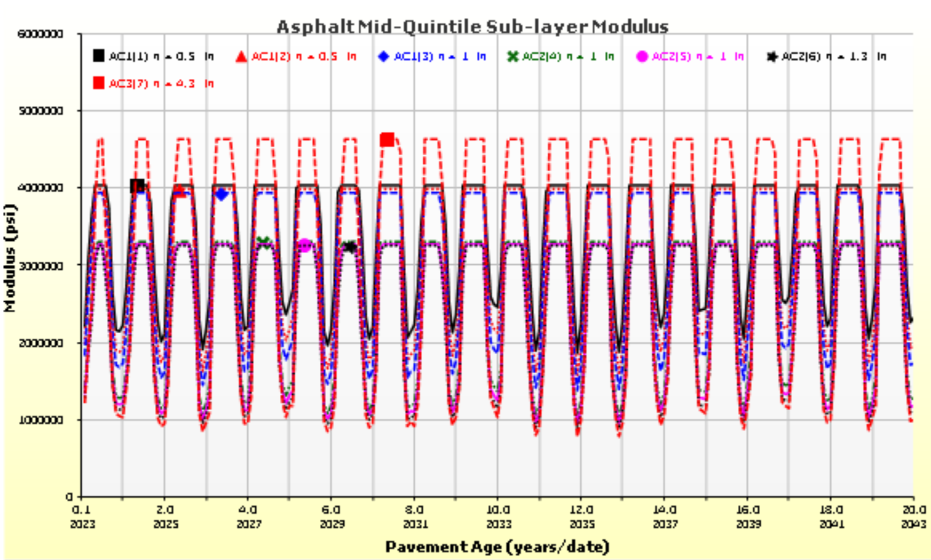


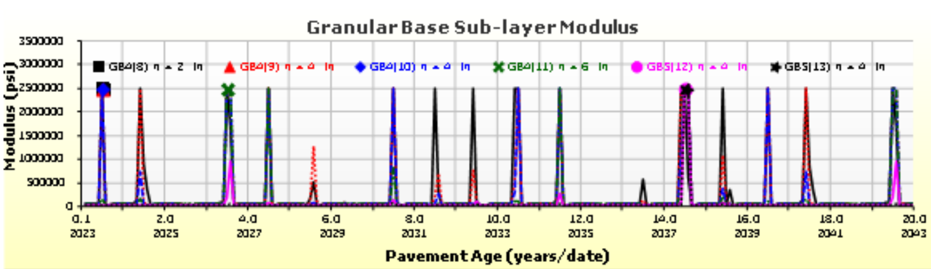
AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)

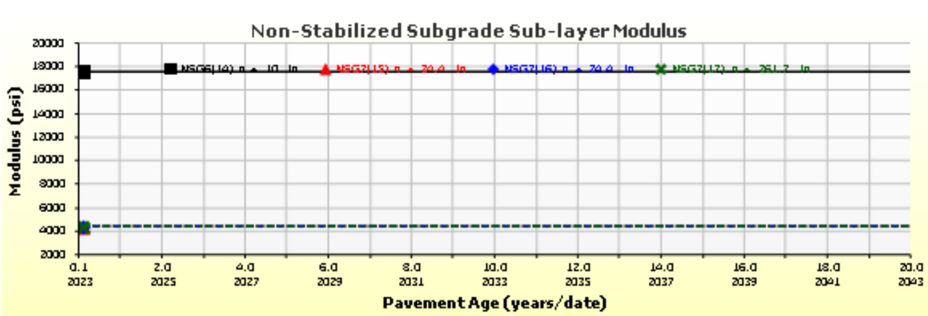


AC Bottom-Up Cracking (Alligator)
Threshold Value
@ 50% Reliability
@ Specified Reliability
Bottom-Up Cracking (%)
Pavement Age (years/date)


Rutting (Permanent Deformation) at 50% Reliability
Total
Subtotal AC
Subtotal Subgrade
Subtotal Base
Rut Depth (in)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Granular Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : 4EMH_64-22

Asphalt		
Thickness (in)	2.0	
Unit weight (pcf)	146.4	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	1 Hz	10 Hz	25 Hz
14	2838283.1	3334118.2	3766841.5	3919629.2
40	1632355.7	2178796.6	2723856.9	2931877.7
70	607108.2	993384.7	1474667.7	1684561.2
100	160848.6	328113.1	599280.9	738853
130	36540.6	88188.9	194588.1	258984.5

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
40	15522432.6	46.1
70	2723528.3	58.4
100	234411.5	69
130	15452.3	77.3
168	885.3	84.4

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	11.5
Air voids (%)	6.1
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.6
Aggregate parameter	0.3313

Identifiers

Field	Value
Display name/identifier	4EMH_64-22
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	64-22
User defined field 2	Used [test] for E/IDT/Dt
User defined field 3	
Revision Number	0

Layer 2 Flexible : 3EMH_64-22

Asphalt		
Thickness (in)	3.3	
Unit weight (pcf)	147.6	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	1 Hz	10 Hz	25 Hz
14	2259900.6	2753660.7	3177786.7	3324297
40	1212821.6	1733458.7	2265760.5	2468893.6
70	410324	740397.3	1185353.4	1385958.1
100	106231	234742.3	466357.7	592731.4
130	27566.1	66765.6	154298.8	210388.3

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
40	15522432.6	46.1
70	2723528.3	58.4
100	234411.5	69
130	15452.3	77.3
168	885.3	84.4

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	10.8
Air voids (%)	5.8
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	3EMH_64-22
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	64-22
User defined field 2	Used [test] for E/IDT/Dt
User defined field 3	
Revision Number	0

Layer 3 Flexible : 2EMH_58-22

Asphalt		
Thickness (in)	4.3	
Unit weight (pcf)	151.6	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	1 Hz	10 Hz	25 Hz
40	1317170.3	1976027.7	2757154.4	3096039
70	367272.1	702162.3	1187239.3	1421849.6
100	72923.3	181766.9	394664.9	516363.8
130	14813.3	41865.3	111025.8	158519

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
40	11843112.7	47.3
70	2023700.3	59.7
100	155618.5	70.2
130	9667.5	78.3
168	610.5	84.8

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.7
Air voids (%)	4.8
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	2EMH_58-22
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	58-22
User defined field 2	Used [pred] for E/IDT/Dt
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : OGDC

Unbound	
Layer thickness (in)	16.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 2)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
33000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	OGDC
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	0.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127
Saturated hydraulic conductivity (ft/hr)	False	4.322e-01
Specific gravity of solids	False	2.7
Water Content (%)	False	6.5

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	9.6111
bf	2.9560
cf	0.8456
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	4.2
#100	
#80	
#60	
#50	
#40	
#30	13.7
#20	
#16	
#10	
#8	23.6
#4	
3/8-in.	
1/2-in.	58.8
3/4-in.	
1-in.	93.5
1 1/2-in.	100.0
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 5 Non-stabilized Base : Sand Subbase

Unbound	
Layer thickness (in)	8.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
20000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Sand Subbase
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	0.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	124.6
Saturated hydraulic conductivity (ft/hr)	False	9.427e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	9.5

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	5.4729
bf	1.9212
cf	0.8511
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	4.6
#100	15.6
#80	
#60	
#50	
#40	
#30	
#20	
#16	
#10	
#8	
#4	
3/8-in.	
1/2-in.	
3/4-in.	
1-in.	99.8
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 6 Subgrade : CL

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Annual representative values
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
17600.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	CL
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	32.5
Plasticity Index	15.2
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	113.5
Saturated hydraulic conductivity (ft/hr)	False	1.334e-05
Specific gravity of solids	False	2.7
Water Content (%)	False	16.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	103.6213
bf	0.7124
cf	0.2475
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	57.5
#100	68.3
#80	
#60	
#50	
#40	90.7
#30	
#20	96.0
#16	
#10	97.7
#8	
#4	99.5
3/8-in.	99.9
1/2-in.	
3/4-in.	
1-in.	
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 7 Subgrade : CL

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Annual representative values
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
4400.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	CL
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	32.5
Plasticity Index	15.2
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	113.5
Saturated hydraulic conductivity (ft/hr)	False	1.334e-05
Specific gravity of solids	False	2.7
Water Content (%)	False	16.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	103.6213
bf	0.7124
cf	0.2475
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	57.5
#100	68.3
#80	
#60	
#50	
#40	90.7
#30	
#20	96.0
#16	
#10	97.7
#8	
#4	99.5
3/8-in.	99.9
1/2-in.	
3/4-in.	
1-in.	
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Calibration Coefficients

AC Fatigue

$$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$$

k1: 3.75
k2: 2.87
k3: 1.46
Bf1: (5.014 * Pow(hac,-3.416)) * 1 + 0
Bf2: 1.38
Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_a^2 + 2.4868 * H_a - 17.342$$

$$C_2 = 0.0172 * H_a^2 - 1.7331 * H_a + 27.428$$

Where:

$H_{ac} = total\ AC\ thickness(in)$

$\varepsilon_p = plastic\ strain(in/in)$

$\varepsilon_r = resilient\ strain(in/in)$

$T = layer\ temperature(^\circ F)$

$N = number\ of\ load\ repetitions$

acRuttingStandardDeviation	0.1481 * Pow(RUT,0.4175)	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.148 Br2:0.7 Br3:1.3
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.148 Br2:0.7 Br3:1.3
AC Layer 3	K1:-2.45 K2:3.01 K3:0.22	Br1:0.148 Br2:0.7 Br3:1.3

Thermal Fracture

$$C_f = \beta_{t1} N\left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: 0.85	Level 1 Standard Deviation: 0.1223 * THERMAL + 400.9
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

$N_f = number\ of\ repetitions\ to\ fatigue\ cracking$

$\sigma_s = Tensile\ stress(psi)$

$M_r = modulus\ of\ rupture(psi)$

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

Unbound Layer Rutting

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

Base Rutting		Subgrade Rutting	
k1: 0.965	Bs1: 0.301	k1: 0.965	Bs1: 0.07
Standard Deviation (BASERUT) 0.0411 * Pow(BASERUT,0.3656)		Standard Deviation (BASERUT) 0.0728 * Pow(SUBRUT,0.5456)	

AC Cracking

AC Top Down Cracking

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0 / 2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

c1: 2.5219	c2: 0.8069	c3: 1
kL1: 64271618	kL2: 0.2855	kL3: 0.011
kL4: 0.01488	kL5: 3.266	

acCrackingTopStandardDeviation
0.3657 * TOP + 3.6563

AC Bottom Up Cracking

$$FC = \left(\frac{6000}{1 + e^{\left(C_1 * C_1' + C_2 * C_2' \log_{10}(D * 100)\right)}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 0.232	c2: (0.867 + 0.2583 * hac) * 0.2204	c3: 6000

acCrackingBottomStandardDeviation
0.2262 + 14.2349/(1+exp(0.2958-0.1441*LOG10 (BOTTOM)))

CSM Cracking

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1: 0	C2: 75	C3: 2	C4: 2

csmCrackingStandardDeviation
CTB*1

IRI Flexible Pavements

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 42.874	C2: 0.102	C3: 0.0081	C4: 0.003

63022-124103_I96_JPCP RECON_10.5in_unstab_CL

File Name: C:\NB\Pavement ME\Analysis\JPCP Final Designs\124103JPCP_MI\63022-124103_I96_JPCP RECON_10.5in_unstab_CL.dgpx

Design Inputs

Design Life: 20 years
Design Type: JPCP

Existing construction: -
Pavement construction: August, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42.665, -83.418

Design Structure

Layer type	Material Type	Thickness (in)
PCC	JPCP	10.5
NonStabilized	OGDC	16.0
Subgrade	CL	Semi-infinite

Joint Design:	
Joint spacing (ft)	14.0
Dowel diameter (in)	1.50
Slab width (ft)	12.0

Traffic

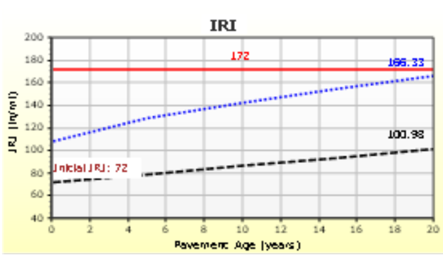
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	8,480
2033 (10 years)	11,459,500
2043 (20 years)	23,267,500

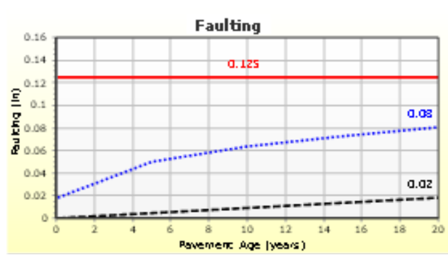
Design Outputs

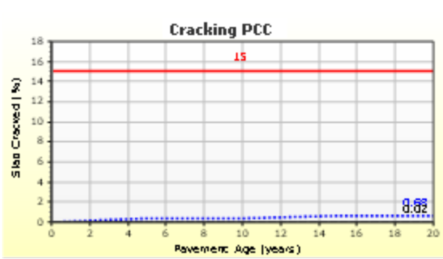
Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	166.33	95.00	96.31	Pass
Mean joint faulting (in)	0.13	0.08	95.00	99.75	Pass
JPCP transverse cracking (percent slabs)	15.00	0.68	95.00	100.00	Pass

Distress Charts







Threshold Value | @ Specified Reliability | @ 50% Reliability

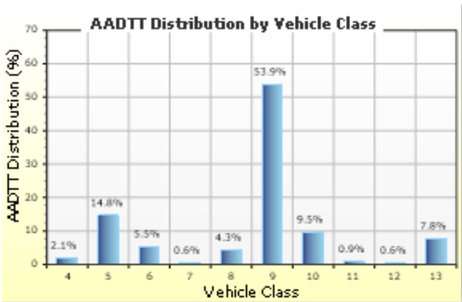
63022-124103_I96_JPCP RECON_10.5in_unstab_CL

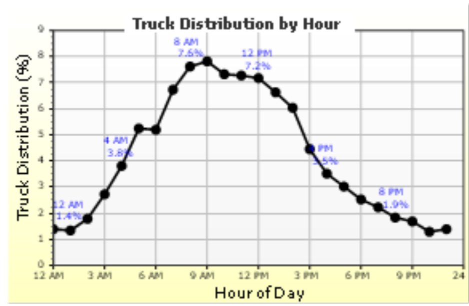
File Name: C:\NB\Pavement ME\Analysis\JPCP Final Designs\124103JPCP_MI\63022-124103_I96_JPCP RECON_10.5in_unstab_CL.dgpx

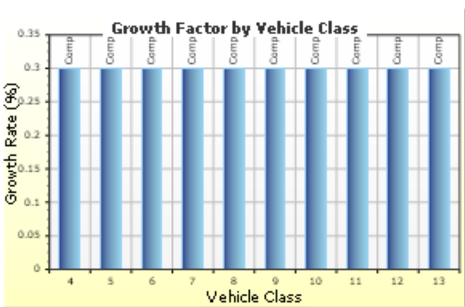
Traffic Inputs

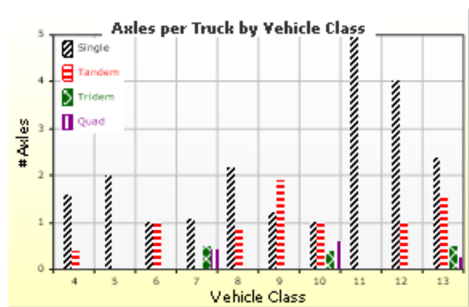
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	8,480	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	3	Percent of trucks in design lane (%):	73.0
		Operational speed (mph)	60.0

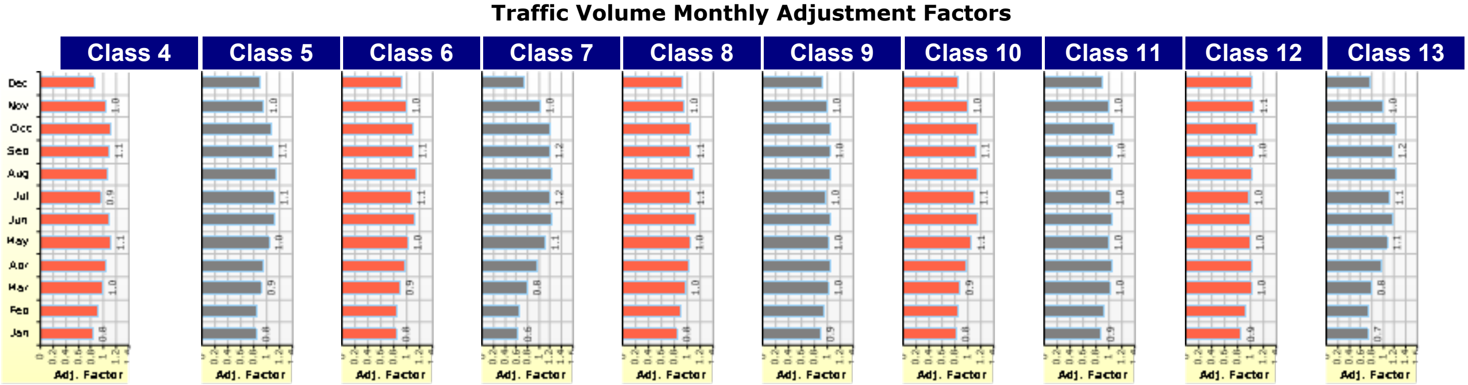








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class 4	5	6	7	8	9	10	11	12	13
January	0.8	0.8	0.8	0.6	0.8	0.9	0.8	0.9	0.9	0.7
February	0.9	0.8	0.8	0.6	0.9	0.9	0.8	0.9	0.9	0.7
March	1.0	0.9	0.9	0.8	1.0	1.0	0.9	1.0	1.0	0.8
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
May	1.1	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.1
June	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.1	1.0	1.2
July	0.9	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.1
August	1.1	1.2	1.1	1.2	1.1	1.1	1.2	1.1	1.0	1.2
September	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.2
October	1.1	1.1	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.2
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0
December	0.8	0.9	0.9	0.8	0.9	0.9	0.8	0.9	1.0	0.8

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor Rate (%)	Growth Factor Function
Class 4	2.1%	0.3%	Compound
Class 5	14.8%	0.3%	Compound
Class 6	5.5%	0.3%	Compound
Class 7	0.6%	0.3%	Compound
Class 8	4.3%	0.3%	Compound
Class 9	53.9%	0.3%	Compound
Class 10	9.5%	0.3%	Compound
Class 11	0.9%	0.3%	Compound
Class 12	0.6%	0.3%	Compound
Class 13	7.8%	0.3%	Compound

Truck Distribution by Hour

Hour	Distribution (%)	Hour	Distribution (%)
12 AM	1.4%	12 PM	7.17%
1 AM	1.33%	1 PM	6.62%
2 AM	1.79%	2 PM	6.01%
3 AM	2.73%	3 PM	4.46%
4 AM	3.79%	4 PM	3.5%
5 AM	5.22%	5 PM	3.04%
6 AM	5.2%	6 PM	2.51%
7 AM	6.75%	7 PM	2.22%
8 AM	7.62%	8 PM	1.85%
9 AM	7.81%	9 PM	1.69%
10 AM	7.34%	10 PM	1.31%
11 AM	7.26%	11 PM	1.38%
		Total	100%

Axle Configuration

Traffic Wander	
Mean wheel location (in)	18.0
Traffic wander standard deviation (in)	10.0
Design lane width (ft)	12.0

Axle Configuration	
Average axle width (ft)	8.5
Dual tire spacing (in)	12.0
Tire pressure (psi)	120.0

Average Axle Spacing	
Tandem axle spacing (in)	51.6
Tridem axle spacing (in)	49.2
Quad axle spacing (in)	49.2

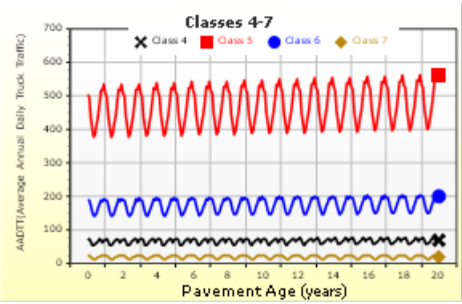
Wheelbase: Value Type / Axle Type	Short	Medium	Long
Average spacing of axles (ft)	12.0	15.0	18.0
Percent of Trucks (%)	17.0	22.0	61.0

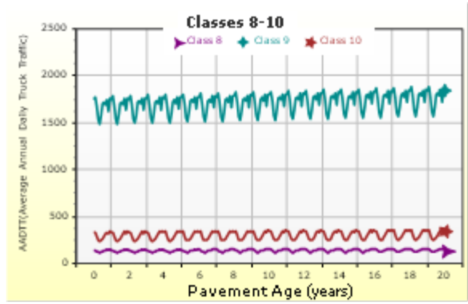
Number of Axles per Truck

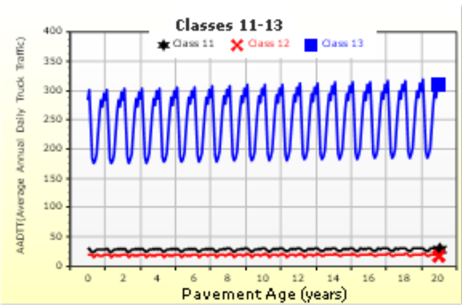
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.6	0.4	0	0
Class 5	2	0	0	0
Class 6	1	1	0	0
Class 7	1.08	0.06	0.51	0.43
Class 8	2.16	0.84	0	0
Class 9	1.21	1.89	0	0
Class 10	1	1	0.4	0.6
Class 11	5	0	0	0
Class 12	4	1	0	0
Class 13	2.4	1.56	0.51	0.27

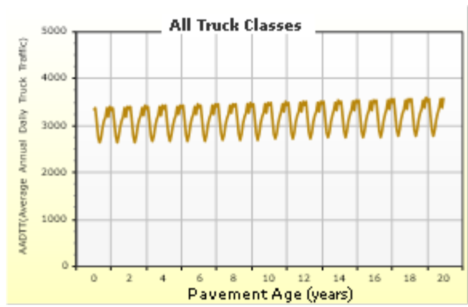
AADTT (Average Annual Daily Truck Traffic) Growth

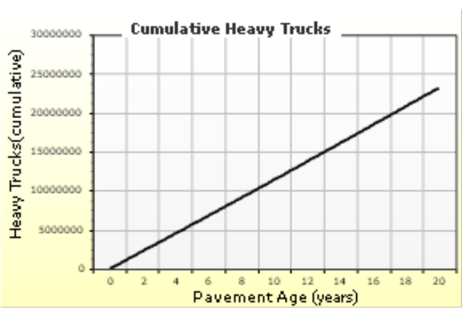
*** Traffic cap is not enforced**







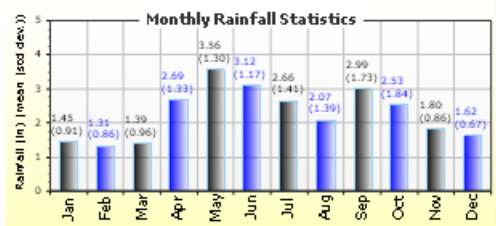




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
PONTIAC, MI	42.66500 -83.41800 971

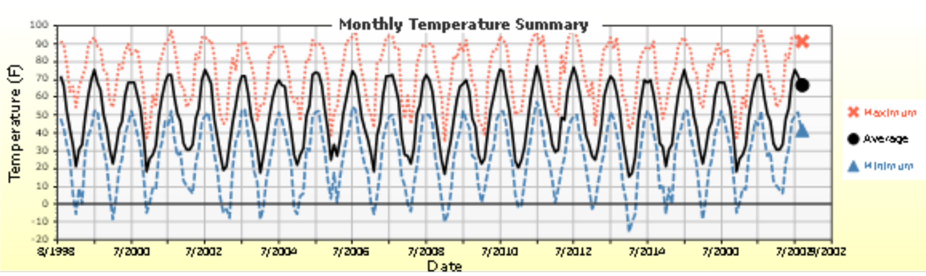


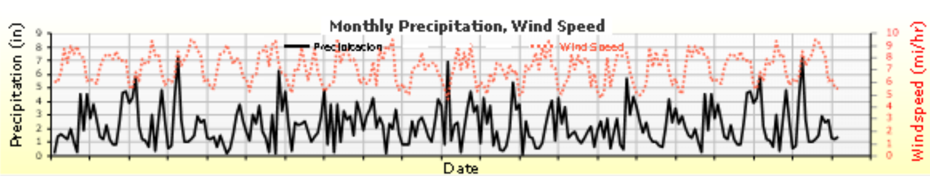
Annual Statistics:

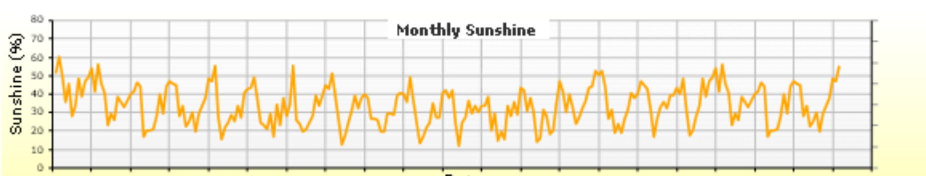
Mean annual air temperature (ºF)	49.16
Mean annual precipitation (in)	27.21
Freezing index (ºF - days)	807.74
Average annual number of freeze/thaw cycles:	57.62

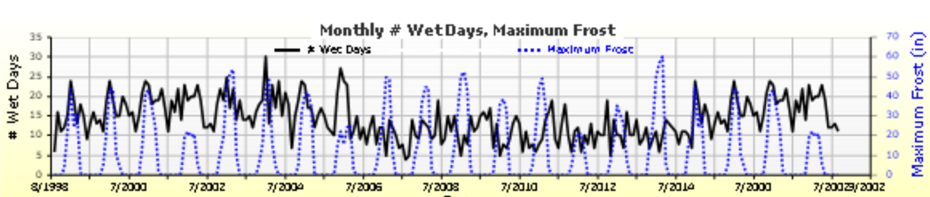
Water table depth (ft) 5.00

Monthly Climate Summary:

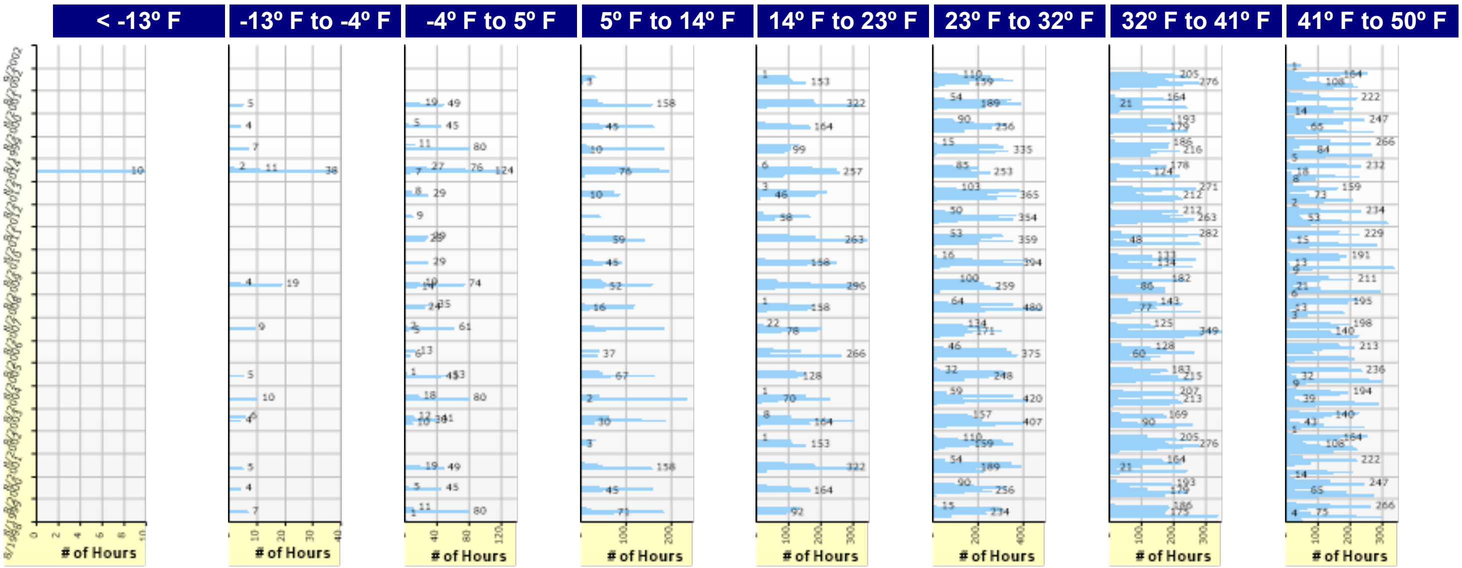


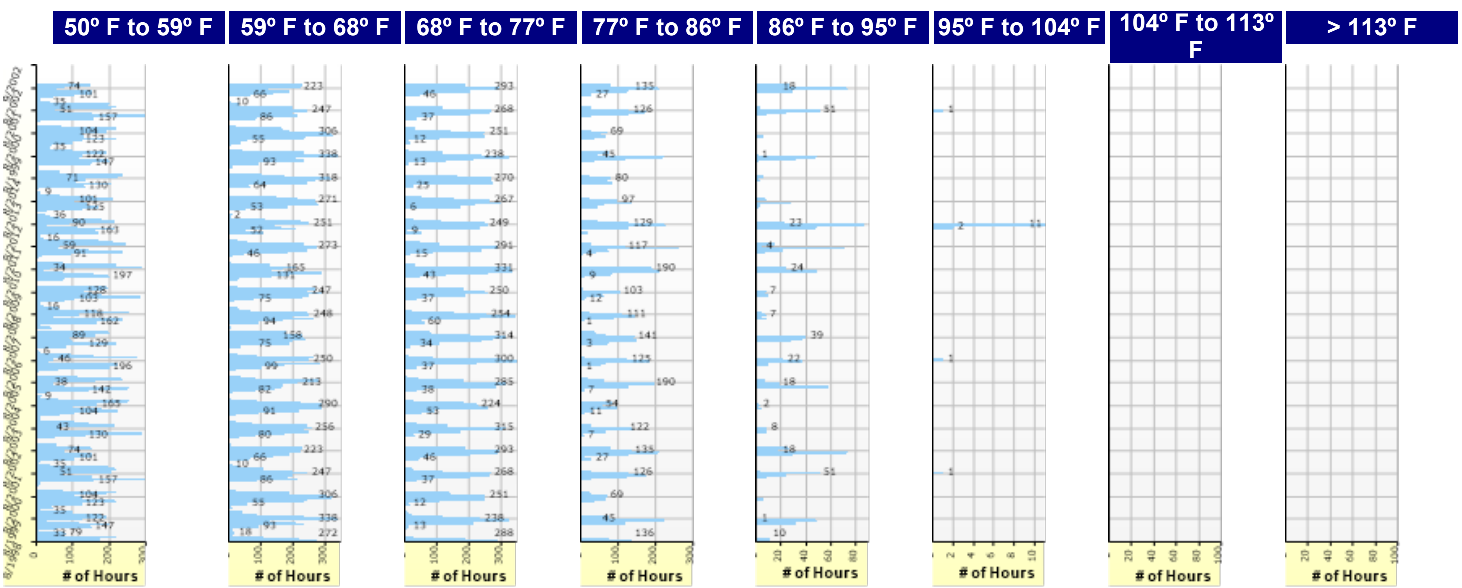






Hourly Air Temperature Distribution by Month:





Design Properties

JPCP Design Properties

Structure - ICM Properties	
PCC surface shortwave absorptivity	0.85

Doweled Joints	
Is joint doweled ?	True
Dowel diameter (in)	1.50
Dowel spacing (in)	12.00

Tied Shoulders	
Tied shoulders	True
Load transfer efficiency (%)	50.00

PCC joint spacing (ft)	
Is joint spacing random ?	False
Joint spacing (ft)	14.00

Widened Slab	
Is slab widened ?	False
Slab width (ft)	12.00

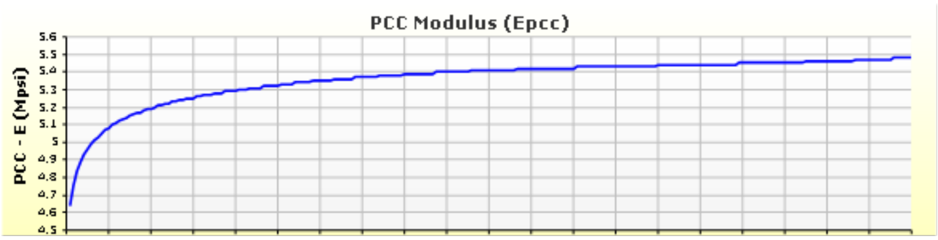
PCC-Base Contact Friction	
PCC-Base full friction contact	True
Months until friction loss	60.00

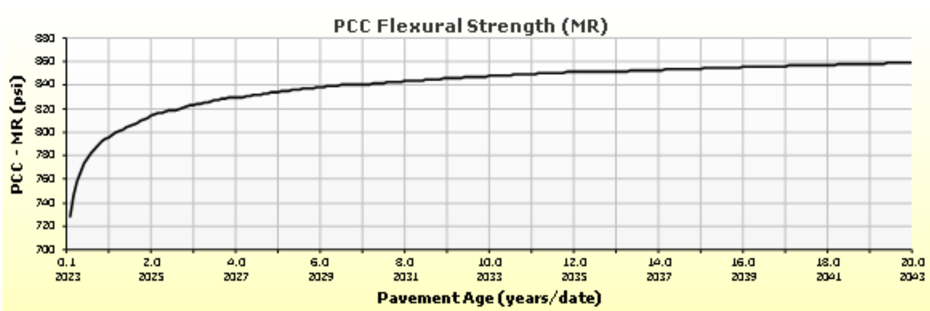
Sealant type	Other(Including No Sealant... Liquid... Silicone)

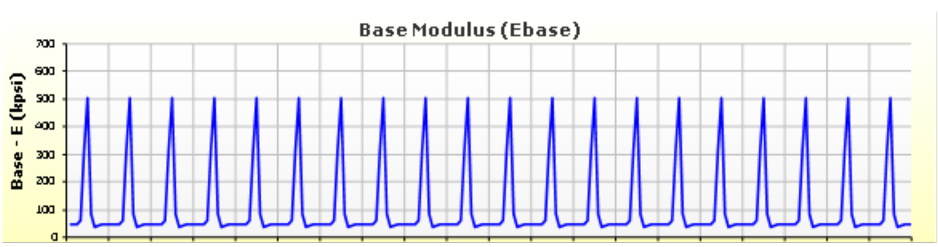
Erodibility index	4

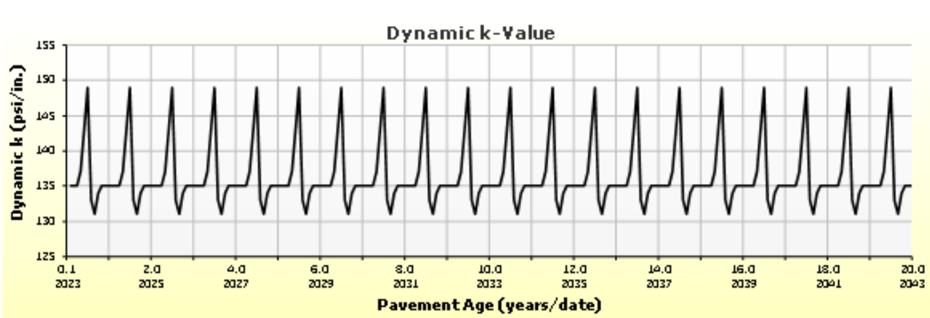
Permanent curl/warp effective temperature difference (ºF)	-10.00

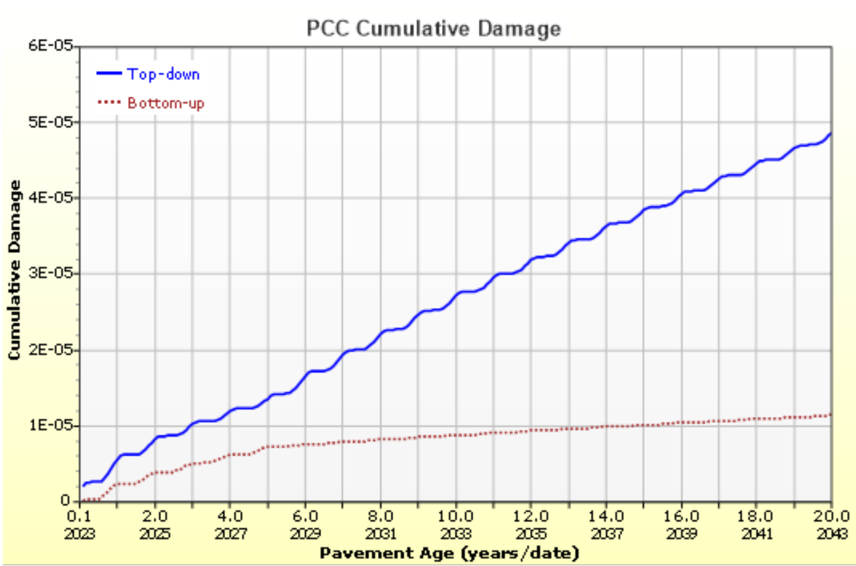
Analysis Output Charts


PCC Modulus (Epcc)
PCC - E (Mpsi)
5.6
5.5
5.4
5.3
5.2
5.1
5
4.9
4.8
4.7
4.6
4.5

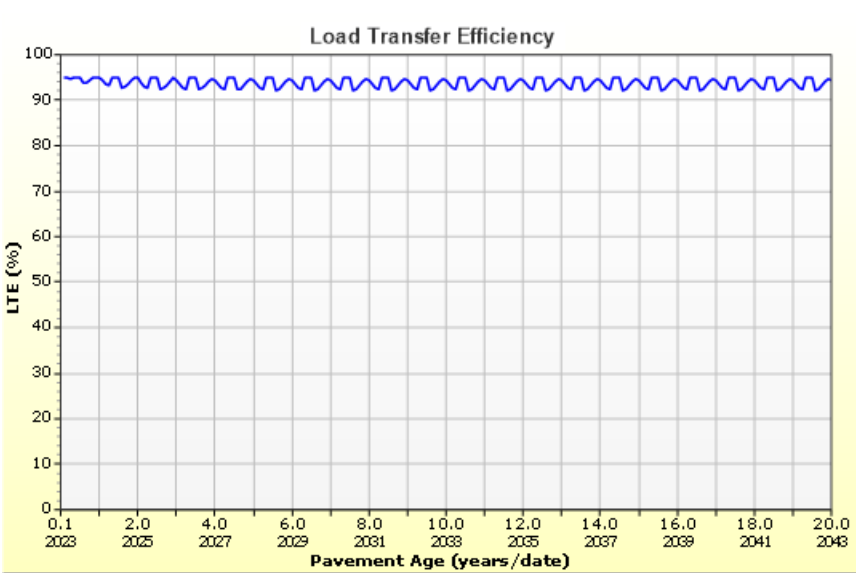

PCC Flexural Strength (MR)
PCC - MR (psi)
880
860
840
820
800
780
760
740
720
700
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Base Modulus (Ebase)
Base - E (kpsi)
700
600
500
400
300
200
100
0


Dynamic k-Value
Dynamic k (psi/in.)
155
150
145
140
135
130
125
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)



PCC Cumulative Damage
Top-down
Bottom-up
Cumulative Damage
6E-05
5E-05
4E-05
3E-05
2E-05
1E-05
0
0.1 2.0 4.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0
2023 2025 2027 2029 2031 2033 2035 2037 2039 2041 2043
Pavement Age (years/date)



Load Transfer Efficiency
LTE (%)
100
90
80
70
60
50
40
30
20
10
0
0.1 2.0 4.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0
2023 2025 2027 2029 2031 2033 2035 2037 2039 2041 2043
Pavement Age (years/date)

Layer Information

Layer 1 PCC : JPCP

PCC	
Thickness (in)	10.5
Unit weight (pcf)	145.0
Poisson's ratio	0.2

Thermal	
PCC coefficient of thermal expansion (in/in/ºF x 10^-6)	5
PCC thermal conductivity (BTU/hr-ft-ºF)	1.25
PCC heat capacity (BTU/lb-ºF)	0.28

Mix		
Cement type		Type I (1)
Cementitious material content (lb/yd^3)		500
Water to cement ratio		0.42
Aggregate type		Limestone (1)
PCC zero-stress temperature (ºF)	Calculated Internally?	True
	User Value	-
	Calculated Value	97.6
Ultimate shrinkage (microstrain)	Calculated Internally?	True
	User Value	-
	Calculated Value	530.8
Reversible shrinkage (%)		50
Time to develop 50% of ultimate shrinkage (days)		35
Curing method		Curing Compound

PCC strength and modulus (Input Level: 3)

28-Day PCC compressive strength (psi)	5600.0
28-Day PCC elastic modulus (psi)	-

Identifiers

Field	Value
Display name/identifier	JPCP
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Non-stabilized Base : OGDC

Unbound	
Layer thickness (in)	16.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 2)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
33000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	OGDC
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	0.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127
Saturated hydraulic conductivity (ft/hr)	False	4.322e-01
Specific gravity of solids	False	2.7
Water Content (%)	False	6.5

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	9.6111
bf	2.9560
cf	0.8456
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	4.2
#100	
#80	
#60	
#50	
#40	
#30	13.7
#20	
#16	
#10	
#8	23.6
#4	
3/8-in.	
1/2-in.	58.8
3/4-in.	
1-in.	93.5
1 1/2-in.	100.0
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 3 Subgrade : CL

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Annual representative values
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
4400.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	CL
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	32.5
Plasticity Index	15.2
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	113.5
Saturated hydraulic conductivity (ft/hr)	False	1.334e-05
Specific gravity of solids	False	2.7
Water Content (%)	False	16.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	103.6213
bf	0.7124
cf	0.2475
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	57.5
#100	68.3
#80	
#60	
#50	
#40	90.7
#30	
#20	96.0
#16	
#10	97.7
#8	
#4	99.5
3/8-in.	99.9
1/2-in.	
3/4-in.	
1-in.	
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Calibration Coefficients

PCC Faulting

$$C_{12} = C_1 + (C_2 * FR^{0.25})$$
$$C_{34} = C_3 + (C_4 * FR^{0.25})$$
$$FaultMax_0 = C_{12} * \delta_{curling} * \left[\log(1 + C_5 * 5.0^{EROD}) * \log\left(P_{200} * \frac{WetDays}{p_s}\right)\right]^{C_6}$$
$$FaultMax_i = FaultMax_0 + C_7 * \sum_{j=1}^{m} DE_j * \log(1 + C_5 * 5.0^{EROD})^{C_6}$$
$$\Delta Fault_i = C_{34} * (FaultMax_{i-1} - Fault_{i-1})^2 * DE_i$$
$$C_8 = DowelDeterioration$$

C1: 0.6	C2: 1.611	C3: 0.00217	C4: 0.00444
C5: 250	C6: 0.2	C7: 7.3	C8: 400
pccReliabilityFaultStandardDeviation			
0.0919 * Pow(FAULT,0.2249)			

IRI-jpcp

C1 - Cracking C2 - Spalling C3 - Faulting C4 - Site Factor	C1: 0.0942	C2: 1.5471
	C3: 1.797	C4: 23.7529
	Reliability Standard Deviation	
	5.4	

PCC Cracking

$$\log(N) = C1 \cdot \left(\frac{MR}{\sigma}\right)^{C2}$$
$$CRK = \frac{100}{1 + C4\, FD^{C5}}$$

Fatigue Coefficients		Cracking Coefficients	
C1: 2	C2: 1.22	C4: 0.415	C5: -0.965
pccReliabilityCrackStandardDeviation			
2.9004 * Pow(CRACK,0.5074)			

Stabilized JPCP Example

63022-124103_I96_JPCP RECON_10.5in_stab_CL

File Name: C:\NB\Pavement ME\Analysis\JPCP Final Designs\124103JPCP_MI\63022-124103_I96_JPCP RECON_10.5in_stab_CL.dgpx

Design Inputs

Design Life: 20 years
Design Type: JPCP

Existing construction: -
Pavement construction: August, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42.665, -83.418

Design Structure

Layer type	Material Type	Thickness (in)
PCC	JPCP	10.5
NonStabilized	OGDC	16.0
Subgrade	CL	12.0
Subgrade	CL	Semi-infinite

Joint Design:	
Joint spacing (ft)	14.0
Dowel diameter (in)	1.50
Slab width (ft)	12.0

Traffic

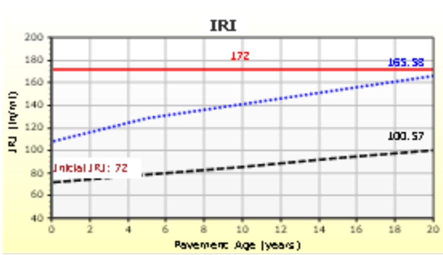
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	8,480
2033 (10 years)	11,459,500
2043 (20 years)	23,267,500

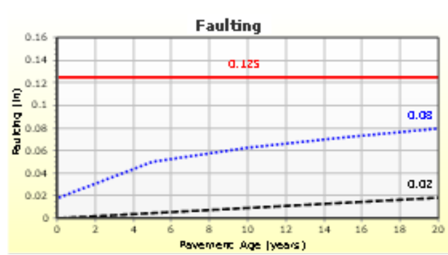
Design Outputs

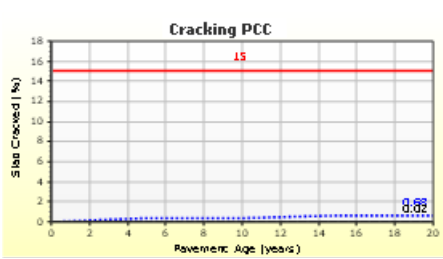
Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	165.58	95.00	96.46	Pass
Mean joint faulting (in)	0.13	0.08	95.00	99.78	Pass
JPCP transverse cracking (percent slabs)	15.00	0.68	95.00	100.00	Pass

Distress Charts







Threshold Value ····· @ Specified Reliability - - - @ 50% Reliability

Reported with version: 2.6.2.2+4140a7281 on: 9/12/2023 9:06 PM

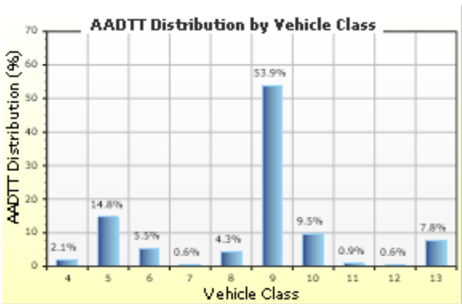
Created with version: N/A on: 4/8/2020 12:00 AM by: J. Schenkel

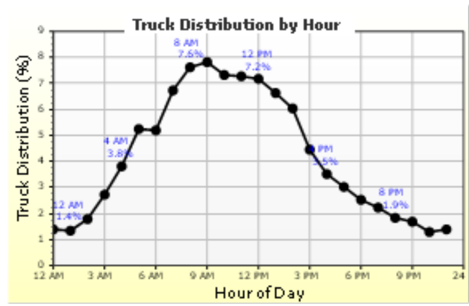
Approved with version: 2.6.2.2+4140a7281 on: 1/1/0001 12:00 AM by:

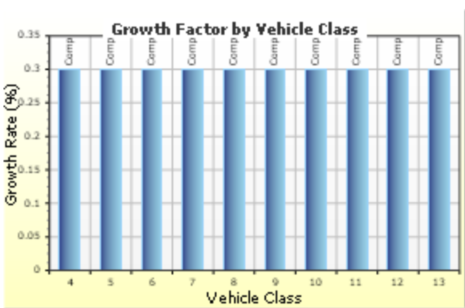
Traffic Inputs

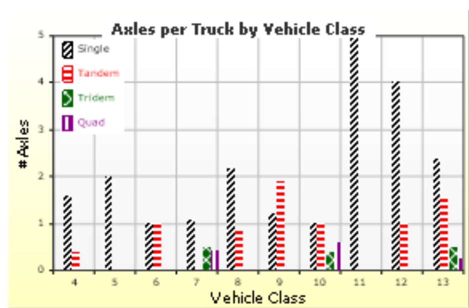
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	8,480	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	3	Percent of trucks in design lane (%):	73.0
		Operational speed (mph)	60.0

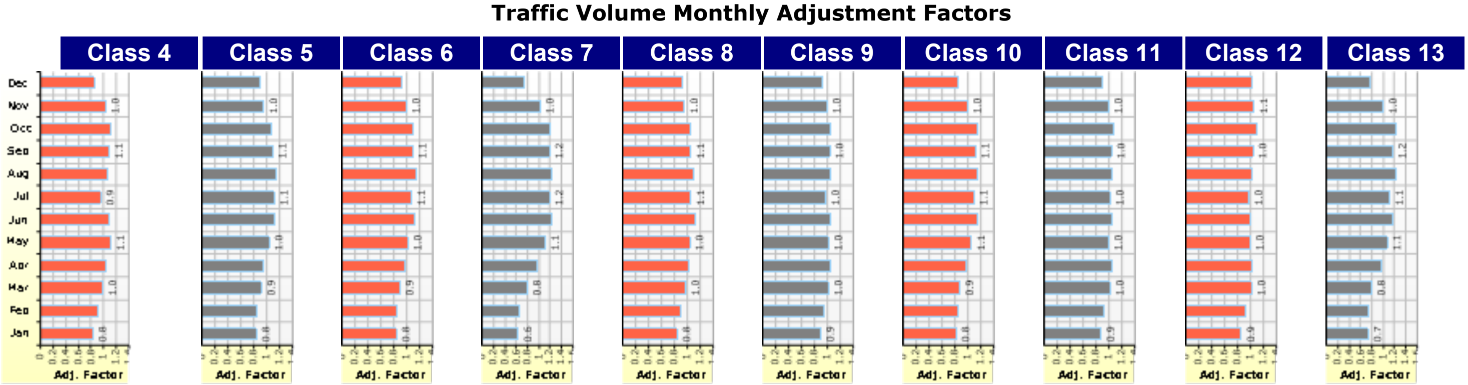








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class 4	5	6	7	8	9	10	11	12	13
January	0.8	0.8	0.8	0.6	0.8	0.9	0.8	0.9	0.9	0.7
February	0.9	0.8	0.8	0.6	0.9	0.9	0.8	0.9	0.9	0.7
March	1.0	0.9	0.9	0.8	1.0	1.0	0.9	1.0	1.0	0.8
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
May	1.1	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.1
June	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.1	1.0	1.2
July	0.9	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.1
August	1.1	1.2	1.1	1.2	1.1	1.1	1.2	1.1	1.0	1.2
September	1.1	1.1	1.1	1.2	1.1	1.0	1.1	1.0	1.0	1.2
October	1.1	1.1	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.2
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0
December	0.8	0.9	0.9	0.8	0.9	0.9	0.8	0.9	1.0	0.8

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor Rate (%)	Growth Factor Function
Class 4	2.1%	0.3%	Compound
Class 5	14.8%	0.3%	Compound
Class 6	5.5%	0.3%	Compound
Class 7	0.6%	0.3%	Compound
Class 8	4.3%	0.3%	Compound
Class 9	53.9%	0.3%	Compound
Class 10	9.5%	0.3%	Compound
Class 11	0.9%	0.3%	Compound
Class 12	0.6%	0.3%	Compound
Class 13	7.8%	0.3%	Compound

Truck Distribution by Hour

Hour	Distribution (%)	Hour	Distribution (%)
12 AM	1.4%	12 PM	7.17%
1 AM	1.33%	1 PM	6.62%
2 AM	1.79%	2 PM	6.01%
3 AM	2.73%	3 PM	4.46%
4 AM	3.79%	4 PM	3.5%
5 AM	5.22%	5 PM	3.04%
6 AM	5.2%	6 PM	2.51%
7 AM	6.75%	7 PM	2.22%
8 AM	7.62%	8 PM	1.85%
9 AM	7.81%	9 PM	1.69%
10 AM	7.34%	10 PM	1.31%
11 AM	7.26%	11 PM	1.38%
		Total	100%

Axle Configuration

Traffic Wander	
Mean wheel location (in)	18.0
Traffic wander standard deviation (in)	10.0
Design lane width (ft)	12.0

Axle Configuration	
Average axle width (ft)	8.5
Dual tire spacing (in)	12.0
Tire pressure (psi)	120.0

Average Axle Spacing	
Tandem axle spacing (in)	51.6
Tridem axle spacing (in)	49.2
Quad axle spacing (in)	49.2

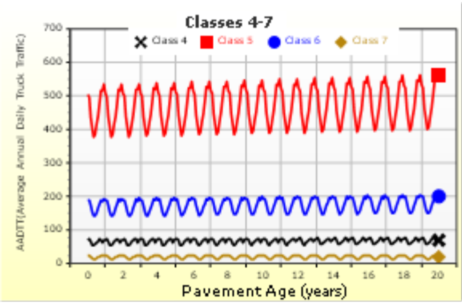
Wheelbase: Value Type / Axle Type	Short	Medium	Long
Average spacing of axles (ft)	12.0	15.0	18.0
Percent of Trucks (%)	17.0	22.0	61.0

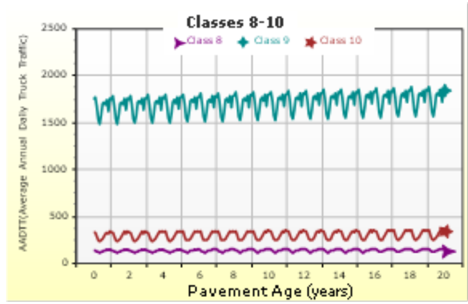
Number of Axles per Truck

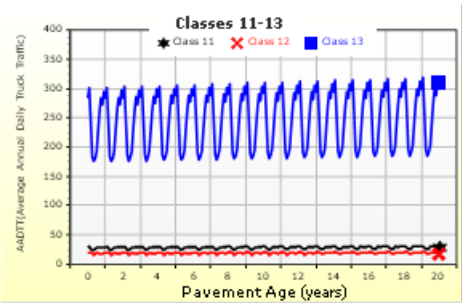
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.6	0.4	0	0
Class 5	2	0	0	0
Class 6	1	1	0	0
Class 7	1.08	0.06	0.51	0.43
Class 8	2.16	0.84	0	0
Class 9	1.21	1.89	0	0
Class 10	1	1	0.4	0.6
Class 11	5	0	0	0
Class 12	4	1	0	0
Class 13	2.4	1.56	0.51	0.27

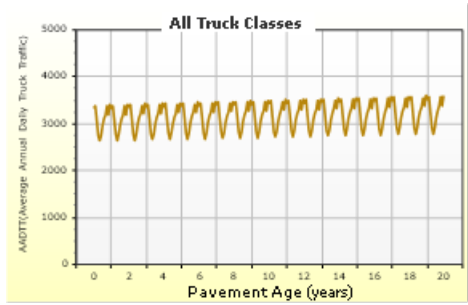
AADTT (Average Annual Daily Truck Traffic) Growth

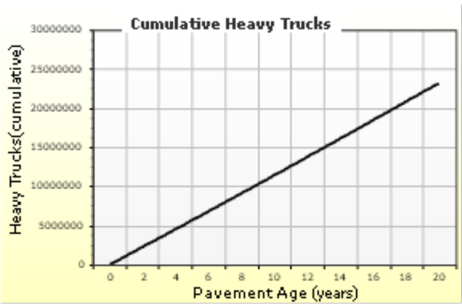
*** Traffic cap is not enforced**







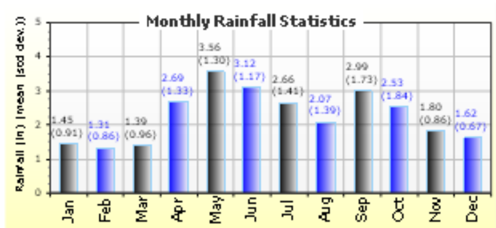




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
PONTIAC, MI	42.66500 -83.41800 971

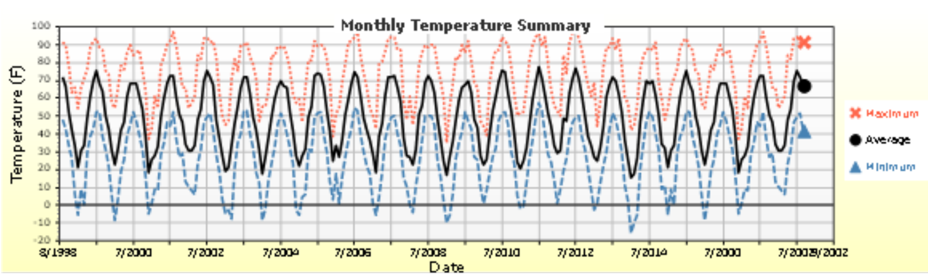


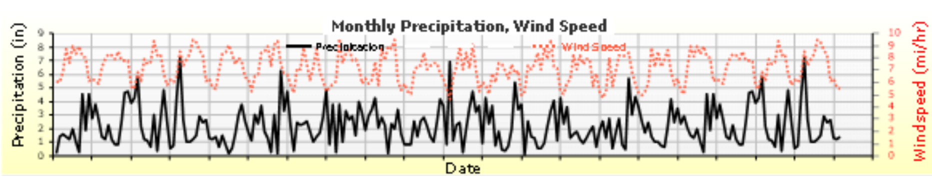
Annual Statistics:

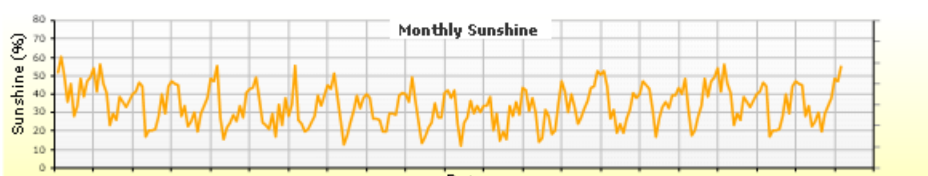
Mean annual air temperature (ºF)	49.16
Mean annual precipitation (in)	27.21
Freezing index (ºF - days)	807.74
Average annual number of freeze/thaw cycles:	57.62

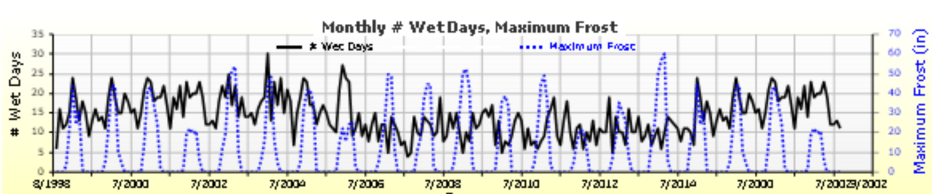
Water table depth (ft) 5.00

Monthly Climate Summary:

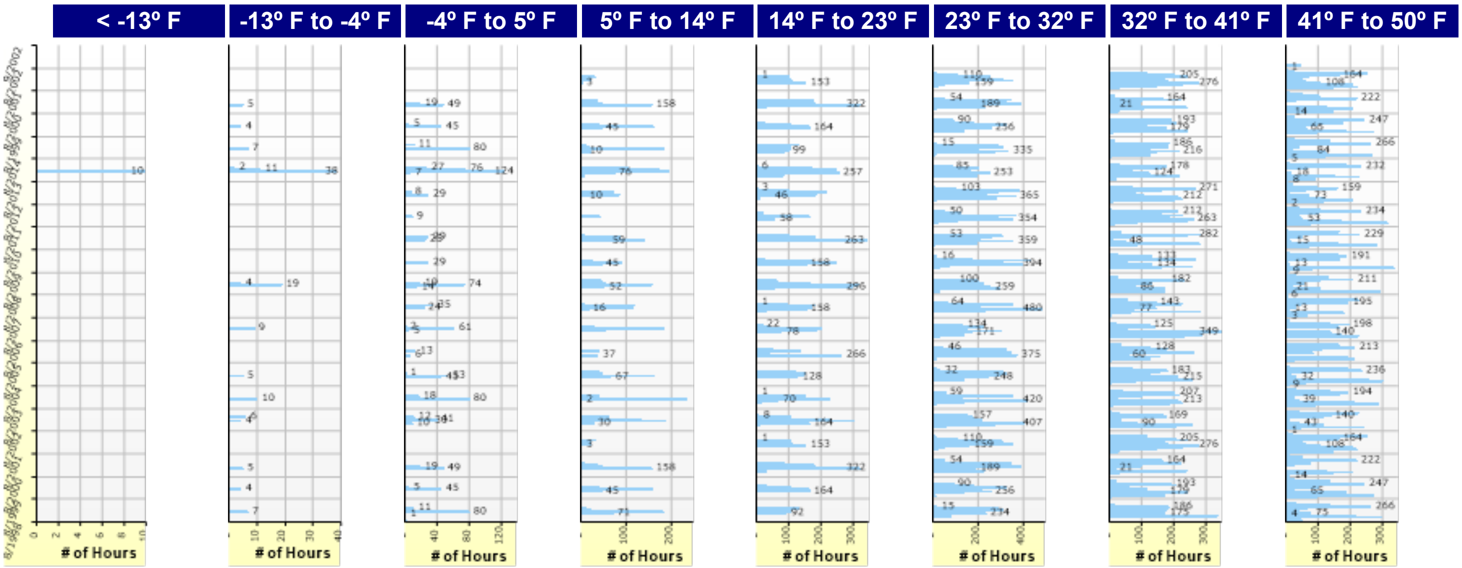


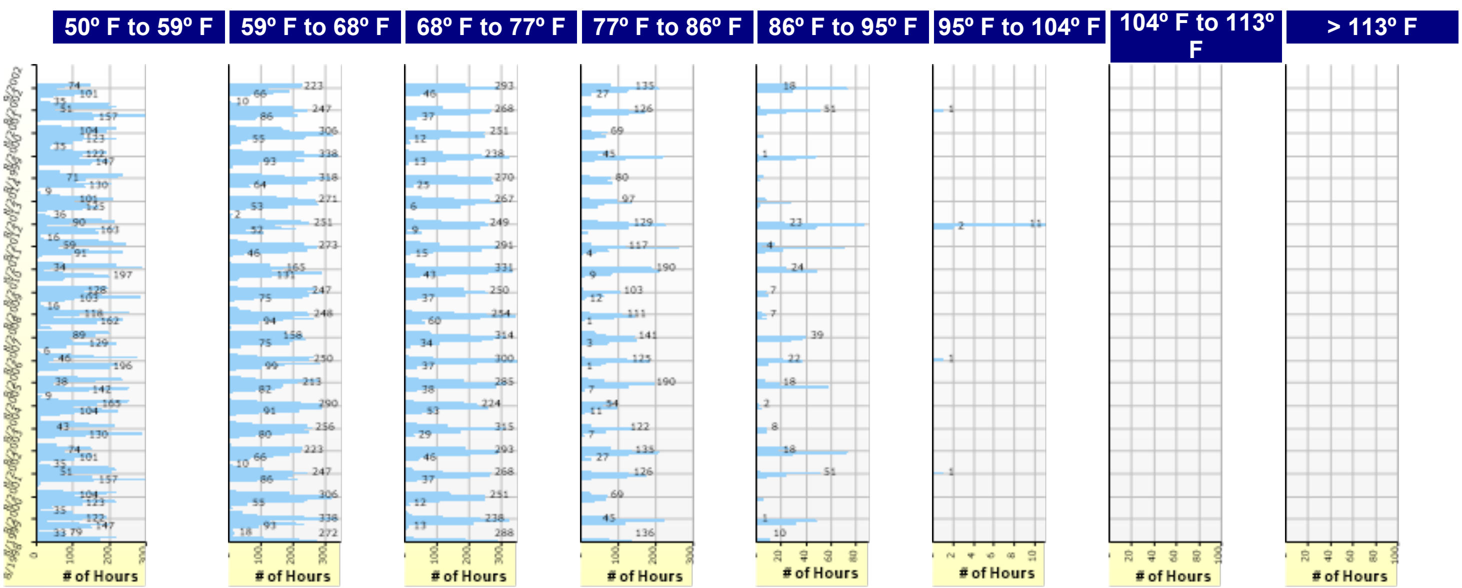






Hourly Air Temperature Distribution by Month:





Design Properties

JPCP Design Properties

Structure - ICM Properties	
PCC surface shortwave absorptivity	0.85

Doweled Joints	
Is joint doweled ?	True
Dowel diameter (in)	1.50
Dowel spacing (in)	12.00

Tied Shoulders	
Tied shoulders	True
Load transfer efficiency (%)	50.00

PCC joint spacing (ft)	
Is joint spacing random ?	False
Joint spacing (ft)	14.00

Widened Slab	
Is slab widened ?	False
Slab width (ft)	12.00

PCC-Base Contact Friction	
PCC-Base full friction contact	True
Months until friction loss	60.00

Sealant type	Other(Including No Sealant... Liquid... Silicone)

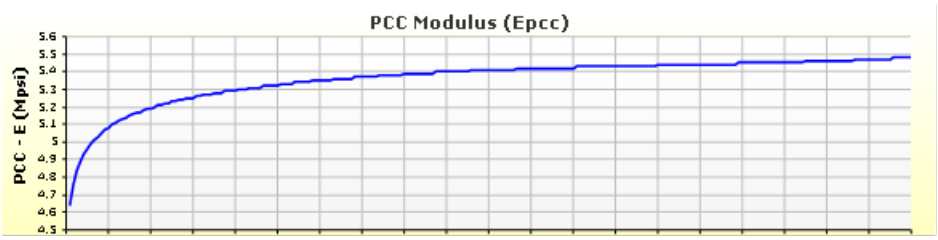
Erodibility index	4

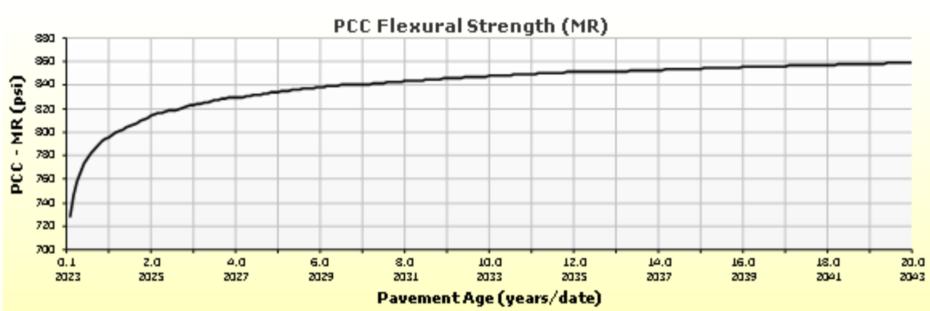
Permanent curl/warp effective temperature difference (ºF)	-10.00

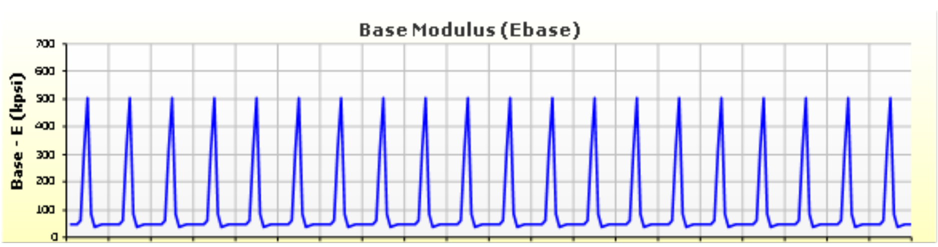
Analysis Output Charts

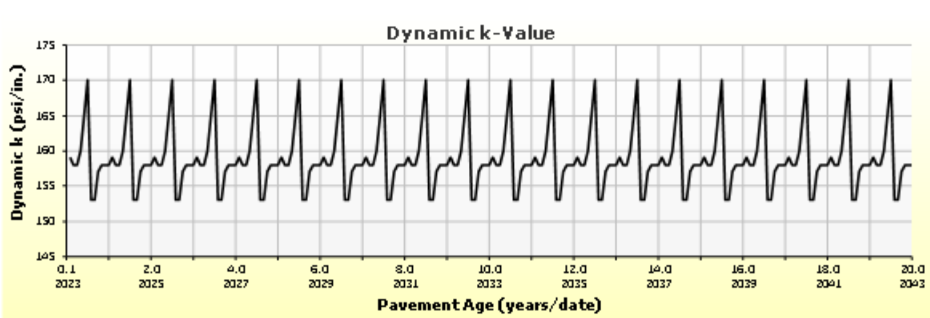
63022-124103_I96_JPCP RECON_10.5in_stab_CL

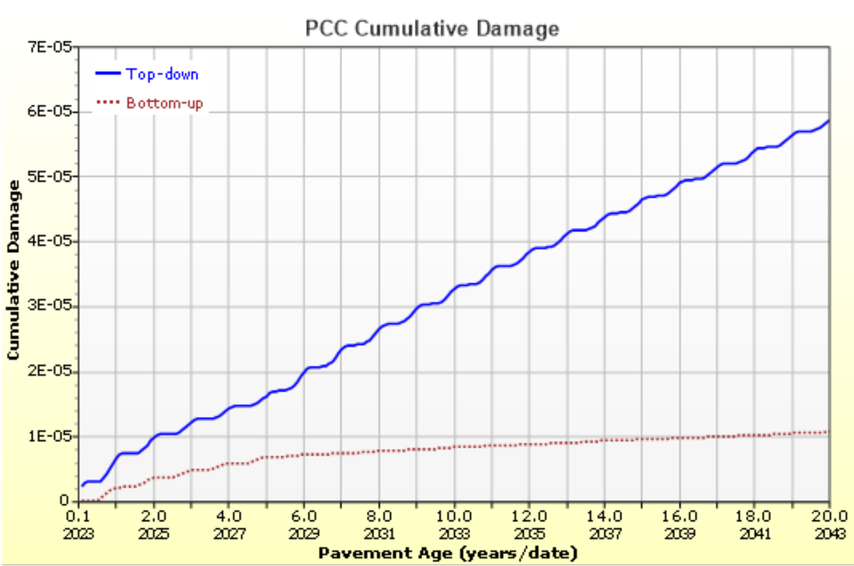
File Name: C:\NB\Pavement ME\Analysis\JPCP Final Designs\124103JPCP_MI\63022-124103_I96_JPCP RECON_10.5in_stab_CL.dgpx



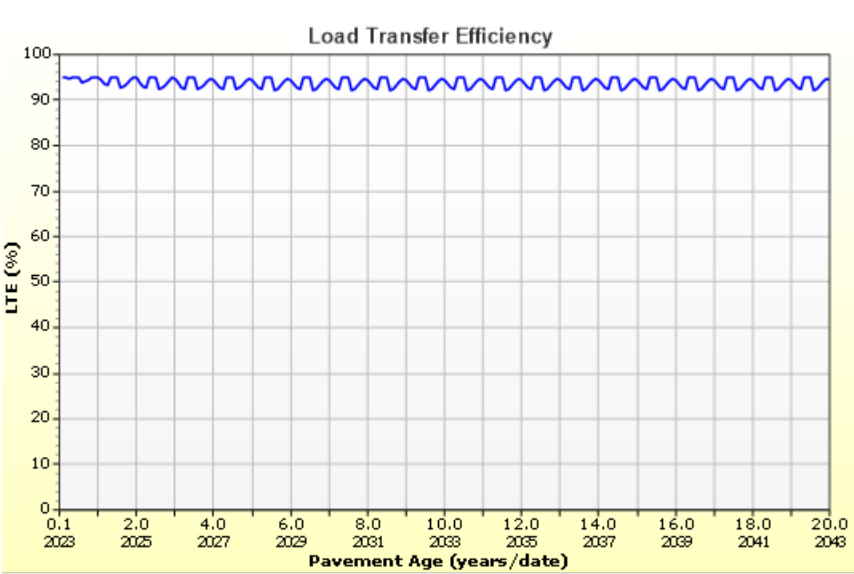








PCC Cumulative Damage
Top-down
Bottom-up
Cumulative Damage
7E-05
6E-05
5E-05
4E-05
3E-05
2E-05
1E-05
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)



Load Transfer Efficiency
LTE (%)
100
90
80
70
60
50
40
30
20
10
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)

Layer Information

Layer 1 PCC : JPCP

PCC	
Thickness (in)	10.5
Unit weight (pcf)	145.0
Poisson's ratio	0.2

Thermal	
PCC coefficient of thermal expansion (in/in/ºF x 10^-6)	5
PCC thermal conductivity (BTU/hr-ft-ºF)	1.25
PCC heat capacity (BTU/lb-ºF)	0.28

Mix		
Cement type		Type I (1)
Cementitious material content (lb/yd^3)		500
Water to cement ratio		0.42
Aggregate type		Limestone (1)
PCC zero-stress temperature (ºF)	Calculated Internally?	True
	User Value	-
	Calculated Value	97.6
Ultimate shrinkage (microstrain)	Calculated Internally?	True
	User Value	-
	Calculated Value	530.8
Reversible shrinkage (%)		50
Time to develop 50% of ultimate shrinkage (days)		35
Curing method		Curing Compound

PCC strength and modulus (Input Level: 3)

28-Day PCC compressive strength (psi)	5600.0
28-Day PCC elastic modulus (psi)	-

Identifiers

Field	Value
Display name/identifier	JPCP
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Non-stabilized Base : OGDC

Unbound	
Layer thickness (in)	16.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 2)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
33000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	OGDC
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	0.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127
Saturated hydraulic conductivity (ft/hr)	False	4.322e-01
Specific gravity of solids	False	2.7
Water Content (%)	False	6.5

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	9.6111
bf	2.9560
cf	0.8456
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	4.2
#100	
#80	
#60	
#50	
#40	
#30	13.7
#20	
#16	
#10	
#8	23.6
#4	
3/8-in.	
1/2-in.	58.8
3/4-in.	
1-in.	93.5
1 1/2-in.	100.0
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 3 Subgrade : CL

Unbound	
Layer thickness (in)	12.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Annual representative values
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
17600.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	CL
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	32.5
Plasticity Index	15.2
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	113.5
Saturated hydraulic conductivity (ft/hr)	False	1.334e-05
Specific gravity of solids	False	2.7
Water Content (%)	False	16.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	103.6213
bf	0.7124
cf	0.2475
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	57.5
#100	68.3
#80	
#60	
#50	
#40	90.7
#30	
#20	96.0
#16	
#10	97.7
#8	
#4	99.5
3/8-in.	99.9
1/2-in.	
3/4-in.	
1-in.	
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Layer 4 Subgrade : CL

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Annual representative values
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
4400.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	CL
Description of object	
Author	
Date Created	1/1/0001 12:00:00 AM
Approver	
Date approved	1/1/0001 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	32.5
Plasticity Index	15.2
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	113.5
Saturated hydraulic conductivity (ft/hr)	False	1.334e-05
Specific gravity of solids	False	2.7
Water Content (%)	False	16.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	103.6213
bf	0.7124
cf	0.2475
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	57.5
#100	68.3
#80	
#60	
#50	
#40	90.7
#30	
#20	96.0
#16	
#10	97.7
#8	
#4	99.5
3/8-in.	99.9
1/2-in.	
3/4-in.	
1-in.	
1 1/2-in.	
2-in.	
2 1/2-in.	
3-in.	
3 1/2-in.	

Calibration Coefficients

PCC Faulting

$$C_{12} = C_1 + (C_2 * FR^{0.25})$$
$$C_{34} = C_3 + (C_4 * FR^{0.25})$$
$$FaultMax_0 = C_{12} * \delta_{curling} * \left[\log(1 + C_5 * 5.0^{EROD}) * \log\left(P_{200} * \frac{WetDays}{p_s}\right)\right]^{C_6}$$
$$FaultMax_i = FaultMax_0 + C_7 * \sum_{j=1}^{m} DE_j * \log(1 + C_5 * 5.0^{EROD})^{C_6}$$
$$\Delta Fault_i = C_{34} * (FaultMax_{i-1} - Fault_{i-1})^2 * DE_i$$
$$C_8 = DowelDeterioration$$

C1: 0.6	C2: 1.611	C3: 0.00217	C4: 0.00444
C5: 250	C6: 0.2	C7: 7.3	C8: 400

pccReliabilityFaultStandardDeviation

0.0919 * Pow(FAULT,0.2249)

IRI-jpcp

C1 - Cracking
C2 - Spalling
C3 - Faulting
C4 - Site Factor

C1: 0.0942	C2: 1.5471
C3: 1.797	C4: 23.7529

Reliability Standard Deviation

5.4

PCC Cracking

$$\log(N) = C1 \cdot \left(\frac{MR}{\sigma}\right)^{C2}$$

$$CRK = \frac{100}{1 + C4\ FD^{C5}}$$

Fatigue Coefficients		Cracking Coefficients	
C1: 2	C2: 1.22	C4: 0.415	C5: -0.965

pccReliabilityCrackStandardDeviation

2.9004 * Pow(CRACK,0.5074)